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DEVELOPMENT AND EVALUATION REPORT: PHYSICAL-CHEMICAL MARINE SANITATION SYSTEM

John M. Heeney, et al

General American Transportation Corporation

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16. ABSTRACT A lab. development-demonstration program was conducted to provide a physical-chemical system for onboard treatment of shipboard wastes. Eval. of hardware developed during the program and analytical results of tests are presented. The treatment system as developed was shown capable of suspended solids removal from raw sewage using the capillary properties of cellulose sponge to draw liquid through a polypropylene filter screen. The use and effectiveness of a pressure-bed filter and coagulants as filtering techniques were also demonstrated. A series of activated carbon adsorption beds were evaluated for removal of dissolved organic materials, and a chlorination unit with no moving parts was shown suitable for disinfection. Evaluation tests of the overall system indicated a range of BOD reductions between 30% and 90% and SS reductions between 50% and 92%. The program indicated the operating characteristics of the major components of the total treatment system and showed a need for the auxiliary filtering or coagulation techniques to handle small-size particles (below 30 microns). The total cost of such a system suitable for treating wastes onboard a marine vessel with a crew of 12 to 20 members, generating up to 2650 liters of wastes per day is estimated to range between $14,500 and $15,000. This report was submitted in fulfillment of Project Number 15020 HJL, Contract 68-01-0116, Phase I, by the General American Transportation Corp., General American Research Division, under the sponsorship of the Environmental Protection Agency. Work was completed as of May 1972.

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PHYSICAL-CHEMICAL MARINE SANITATION SYSTEM

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment -- air, water, and land. The National Environmental Research Centers provide this nultidisciplinary focus through programs engaged in

- o studies on the effects of environmental contaminants on man and the biosphere, and
- o a search for ways to prevent contamination and to recycle valuable resources.

Research studies on effective waste management transportation and recreational sources have involved the development of technology for the economic treatment of wastewaters (including bilge and ballast discharges) from watercraft. Emphasis of investigations have been on treatment effectiveness, operation and maintenance requirements, safety aspects, and overall costs.

A. W. Breidenbach, Ph.D.
Director
National Environmental
Research Center, Cincinnati

ABSTRACT

A laboratory development and demonstration program was conducted to provide a physical/chemical system for onboard treatment of shipboard wastes. Evaluation of hardware developed during the program and analytical results of the tests are presented.

The treatment system as developed was shown capable of suspended solids removal from raw sewage using the capillary properties of cellulose sponge to draw liquid through a polypropylene filter screen. The use and effectiveness of a pressure-bed filter and coagulants as filtering techniques, were also demonstrated. A series of activated carbon adsorption beds were evaluated for removal of dissolved organic materials, and a chlorination unit with no moving parts was shown suitable for disinfection. Evaluation tests of the overall system indicated a range of BOD reductions between 30% and 90% and SS reductions between 50% and 92%.

The program indicated the operating characteristics of the major components of the total treatment system, and showed a need for the auxiliary filtering or coagulation techniques to handle small size particles (below 30 microns).

The total cost of such a system suitable for treating wastes onboard a marine vessel with a crew of 12 to 20 members, generating up to 2650 liters of wastes per day is estimated to range between $14,500 and $15,000.

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CONTENTS

Section		Page
I	Conclusions	1
II	Recommendations	3
III	Introduction	5
IV	System Design and Development	11
V	System Performance Tests	41
VI	Evaluation of System Performance	57
VII	Economic Analysis	65

FIGURES

		Page
1	MOVING SCREEN FILTER WASTE TREATMENT SYSTEM	8
2	LIQUID SOLIDS SEPARATION	12
3	LABORATORY SYSTEM SINGLE-BELT SPONGE AND SCREEN	16
4	LABORATORY PROTOTYPE FILTER EQUIPMENT ARRANGEMENT	17
5	FILTER BELTS	19
6	DUAL-BELT SYSTEM AND DRIVE ASSEMBLY	20
7	PRESSURE BED FILTER OPERATION	22
8	FULL SCALE MSF WASTE TREATMENT SYSTEM	25
9	MAIN FEED TANK	26
10	FEED TANK LEVEL CONTROLS	27
11	ROTARY FEEDER VALVE	29
12	MOVING SCREEN FILTER (MSF) ASSEMBLY DRAWING	30
13	ROTATING BRUSH	32
14	MSF DRIVE ASSEMBLY AND HOUSING	34
15	HOUSING AND DRIVE PANEL REMOVED	35
16	MSF SUPPORT FRAME SLIDE ARMS	36
17	CARBON BED CONFIGURATION	38
18	CHLORINATOR	40

TABLES

No.		Page
1	Single Belt Moving Filter	42
2	Prototype Dual Belt MSF with One 15-cm Diameter, 75-cm Deep Carbon Column	42
3	Size of Media Tested in Bed Filters	43
4	Reduction of Suspended Solids: MSF and Filter Bed Configurations	44
5	Reduction of Suspended Solids: MSF and Pressure Bed Filters	45
6	Performance of Two Carbon Beds in Series: MSF and Pressure Bed Filters	46
7	SS and BOD Removal Tests: MSF, Pressure Filter, and Two Carbon Beds in Series (Raw Sewage Pumped Centrifugally from Sump Basin)	48
8	SS and BOD Removal Tests: MSF Treatment System with Vacuum Transfer of Wastes	51
9	Coagulant Jar Tests	53
10	SS and BOD Removal Tests: MSF Treatment System with Coagulant Addition	55

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SECTION I

CONCLUSIONS

The conclusions presented in this section concerning the Moving Screen Filter (MSF) waste treatment system are based on operating performance during onshore evaluation tests of both laboratory and full-scale treatment systems. All tests were conducted at GARD research facilities.

1. In processing a synthesized raw sewage mixture of food wastes and toilet wastes considered typical (500-1000 mg/l each of SS and BOD) of shipboard sewage on a marine vessel with 12 to 20 crew members, the MSF waste treatment system, including the pressure bed-filter or coagulant filtering aids, achieved the following levels of performance during selected operating tests of short duration, ranging from two to four hours:

SS Removal Efficiency:	88% to 92%
BOD Removal Efficiency:	86% to 95%

2. When processing raw sewage containing no food wastes but only toilet wastes (200 to 700 mg/l SS and 200-400 mg/l BOD) transported by turbulent flow, and with no pressure-bed filter or coagulants as auxiliary filtering aids, the MSF waste treatment device achieved the following average performance levels during the majority of evaluated tests:

SS Removal Efficiency:	50% to 70%
BOD Removal Efficiency:	30% to 60%

3. SS removal efficiency by the MSF was dependent on the particle size in the raw wastes entering the treatment system. Particles below 30 microns in diameter were not readily removed by the moving screen filter alone. These particles resulted primarily from mechanical break-up of the fecal wastes when pumped to the system. To achieve an SS removal over 90%, large amounts of particles below 30 microns should be prevented from forming. This can be achieved if gravity transfer is used in place of pumped transport. Alternatively, if turbulent transport of wastes cannot be avoided and particle size is below 30 microns, SS removal efficiency can be improved by using a pressure-bed filter in addition to the MSF, or by adding coagulants such as lime (CaO) to the wastes entering the MSF.

4. All system operations produced a filtered solids slurry easily pumped to storage for later shoreside disposal or for feed to onboard incineration.

5. BOD removal efficiency was shown to be dependent on solids removal of the filter system and the size of the carbon adsorption bed. SS concentrations between 50-100 mg/l entering the carbon beds were necessary to prevent clogging and maintain effective BOD reduction. BOD removals of 90 percent or greater were achieved by a pressure-bed filter and a coagulant used in conjunction with the MSF to lower the SS to the 50-100 mg/l range, and carbon beds operated in an upflow configuration with 10 to 20 minutes contact time.

6. A pressure-bed of compressible polystyrene granules was shown to be highly effective in the removal of suspended solids in the size range below 30 microns at influent SS levels below 250 mg/l. Cycled operation with backwashing of the filter media as required achieved better than 65% removals. However, slime growth within the anaerobically operating bed inhibited backwashing and shortened the on-stream filtering cycle time. The pressure-bed filter was shown more effective than gravity bed filters.

7. Operation of the MSF system with coagulants showed lime and caustic as more favorable additives than commercially available coagulants and polyelectrolytes; operation at pH values between 11 and 12 in the raw wastes entering the MSF appeared appropriate. The other additives investigated included alum, magnesium chloride, ferric chloride, Primafloc C-7, and Magnafloc 521-C.

8. Mechanical operation of the complete MSF treatment system showed the feasibility of the overall design, and the suitability of system components for automatic operation. Filter screen and absorbent sponge belts were shown to be desirable and adequate for continuous operation. Belt life was estimated at two months of continuous operation.

9. The feasibility of a hypochlorite tablet chlorinator using no moving parts was demonstrated. The unit based upon a water-syphon principle operated on demand and was capable of accommodating varied liquid flow rates. In a limited sequence of tests, the exit coliform density ranged from below 30 and up to 90 MPN/100 ml, with a residual chlorine level of 10 mg/l and a chlorination contact time between 15 and 20 minutes.

10. The initial cost of the system was estimated at $9,700 with an installation cost of approximately $4,800. Operating and maintenance costs are estimated at $115 and $123 per month, respectively, exclusive of solids handling costs.

SECTION II

RECOMMENDATIONS

The recommendations presented in this section are based on the same performance and operating conditions discussed in Section I.

1. Determine feasibility of developing a screen filter material with smaller effective pore size than 30 microns, preferably capable of filtering 1 to 2 micron particles.

2. Investigate feasibility of operating 30-micron filter with a material which could act as a filter-aid to filter out 1 to 2 micron particles.

3. Conduct survey of relevant marine vessel toilet installations to determine:

   a. feasibility of low velocity gravity drainage of toilet wastes to treatment system, and

   b. feasibility of separate drainage for toilet wastes and galley-shower-lavatory wastes, so that toilet wastes can be concentrated or pretreated with coagulant prior to feed into treatment system.

4. Investigate techniques for slime growth control in the pressure bed filter and for more consistent SS and BOD removal by the total MSF system. A typical candidate technique would be to operate the MSF system with fluidized bed carbon adsorption columns, and with pressure bed filter located after chlorinator; the objectives of this arrangement of components would be effective SS removal by the pressure bed filter with slime growth inhibited by chlorination, and effective soluble BOD adsorption without carbon bed plugging.

5. Develop suitable feeder mechanism for adding powdered lime coagulant to raw sewage wastes entering the screen filter.

6. Investigate feasibility of incorporating an onboard incinerator to dispose of the filtered solids collected by the MSF system.

SECTION III

INTRODUCTION

Shipboard Treatment of Wastes

The improvement and enhancement of the nation's waterways requires that all major sources of water pollution be brought under control. Municipalities and industries are responding to the public's demands for improved discharge standards. As a consequence, it is reasonable to expect that vessels using the nation's waterways will be restrained from discharging untreated or only partially treated wastes overboard.

At the present time there are two general approaches for treatment of wastes: (1) total retention in storage tanks aboard ship, and (2) processing of wastes with overboard discharge of a treated effluent. Total retention is practical where the entire volume of wastes stored is low, in the range of 4 to 8 liters per man day. This situation exists generally where toilet wastes are stored, and where no shower, lavatory, or galley facilities are used aboard the vessel.

In nearly all other situations where toilet, lavatory, shower, laundry, and galley facilities are available, the amount of water used daily has been estimated to average 133 liters per man, based on Bioastronautics Data Book (NASA SP 3006), Paul Webb, Editor, 1964. Because of the large tank sizes needed, storage of these volumes is impractical for most vessels and suitable shore facilities properly located along the course of vessel operation are required for periodic discharge of stored wastes.

For situations where 133 liters/man-day of wastes are generated, some form of onboard wastes treatment is needed. Where sufficient energy is available, the water may be evaporated, and the concentrated residues stored or incinerated. Alternately, the total volume of water may be treated by biological or physical-chemical processes with overboard discharge of a treated effluent.

Various treatment methods now in use aboard larger marine vessels include the following singly, or in combinations: (1) evaporation, (2) biological processing, (3) maceration, (4) centrifuging, (5) filtration, (6) chemical or electrolytic coagulation-flocculation, (7) carbon adsorption, (8) chlorination, and (9) ozonation. Of these, the biological systems are excessively large and subject to slow startup, the evaporative systems require high energy inputs unless integrated with toilet water makeup, and the physical systems usually are complex and require high power inputs. The chemical and electrolytic systems also are complex and require integration with physical systems.

Of the onboard treatment systems which are available and meet current discharge standards, none entirely meet the needs of intermediate and small sized vessels with water usage rates ranging from several hundred to several thousand liters per day. On vessels of this size, the availability of space, power, and maintenance facilities is generally quite limited.

Program Scope

The scope of the program concerns developing an onboard physical-chemical treatment system suitable for handling wastes from intermediate and small size marine vessels. The performance criteria for the treatment system are as follows:

1. Achieve 90% reduction of suspended solids (SS) and biochemical oxygen demand (BOD),
2. Reduce the coliform level to below 240 MPN/100 ml,
3. Process 2650 liters of wastes per day.

The treatment system was to be developed and tested to show operating capabilities, and to evaluate suitability for use aboard a marine vessel.

Contract 68-01-0116, Devices for Onboard Treatment of Waste from Vessels, was divided into two phases. Development and laboratory testing of the treatment system was scheduled in Phase I, and demonstration of the system aboard a vessel is scheduled in Phase II.

The program plan for Phase I included the following tasks:

1. Engineering evaluation and system analysis
2. System design
3. System fabrication and assembly
4. Performance testing
5. System modification and refurbishment
6. Analysis and summary of test data
7. Phase I performance report.

Technical Approach and System Description

The method selected for treating shipboard waste operates in three stages:

1. Separation of solids from liquids by screen filtration

2. Carbon adsorption to remove dissolved and colloidal solids

3. Chlorination to reduce coliform content.

This method was selected on the basis of the following criteria:

1. The system has a high processing capacity but requires a relatively small space for installation.

2. System power requirements are low.

3. The system is simple and would not require a specially trained operator.

3. The system can be started and stopped as required with no loss in efficiency.

To achieve operating design objectives, a system was developed as shown in the schematic drawing in Figure 1. The full-scale system developed has a nominal capacity of 2650 liters per day but when operated at accelerated rates can process up to 5700 liters per day.

Ideally, the treatment system would be located to permit gravity drainage of sanitary waste into the feed tank, to minimize break-up or decomposition of fecal wastes. Other waste streams containing solids which do not break apart or deteriorate in transit could be pumped to the feed tank as required.

Sewage in the wastes feed tank is delivered to a moving screen filter (MSF) through a single cavity rotary feeder. The rotary feeder transfers solids up to 5 cm in diameter and maintains a constant feed rate to the filter.

Solids are separated from liquid by the moving screen filter (MSF). Liquid is drawn through the filter by a sponge below the filter which removes particles larger than 30 microns. Solids are retained on top of the filter screen and are removed and transferred by a rotary brush into a collection trough; the screen in then rinsed with spray water to prevent blinding of the cloth, and rinsed solids are returned to the feed tank. The sewage filtrate which passes through the screen is absorbed by the underlying sponge; the liquid is then removed from the sponge at the wringer roll and pumped to carbon columns for further processing. An optional pressure filter may be included after the screen filter when needed to handle particularly small size suspended solids particles. The carbon columns treat the filtrate by adsorbing dissolved and colloidal solids. The filtrate leaving the carbon columns then enters the chlorination tank for the final treatment step. The effluent leaving the chlorination tank is discharged overboard.

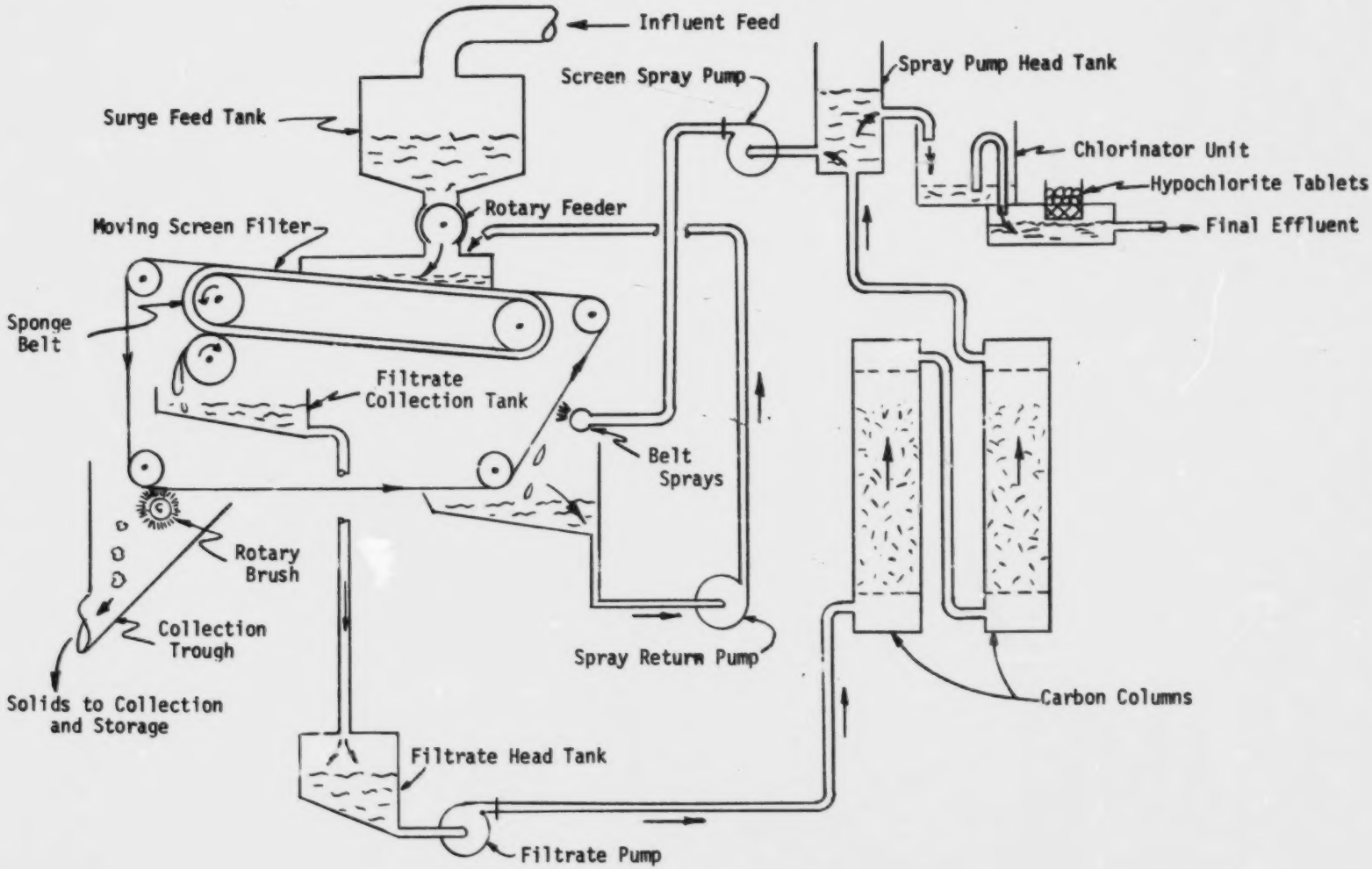


Figure 1 MOVING SCREEN FILTER WASTE TREATMENT SYSTEM

For the full-scale treatment system various design parameters were developed to allow operation of the system on a continuous basis, but with fluctuating incoming volumes and compositions of raw sewage. Based on general shipboard operating routines, various peak flow rates and volume accumulations were established and tankage sizes were determiend. For emergency operations the tankage sizes were modified to allow for filtration at double the nominal daily capacity.

The operation of various streams within the MSF system were determined and flow rates were established through the primary flow control components. In addition, preliminary estimates were prepared of the power requirements for the total system. The initial estimate of design parameters for the system was as follows:

Design Parameters

Volume	
Inlet Surge/Feed Tank	760.0 l
Filtrate Head Tank	5.7 l
Carbon Columns (6)	26.5 l
Spray Pump Head Tank	19.0 l
Flow	
Rotary Feed Valve	5.7 l/min
Moving Screen Filter	5.7 l/min
Filtrate Pump	3.8 l/min
Screen Spray Pump	1.9 l/min
System Discharge	3.8 l/min
Power	
Motors and Controls	1.0 KW

SECTION IV

SYSTEM DESIGN AND DEVELOPMENT

In the development of the three major stages in the treatment process, namely filtering, adsorption of dissolved organics, and disinfection, the most important was the development of an efficient filtration process to remove the bulk of the sewage solids prior to treatment by the final stages. The filtration method used in this system was based on a liquid/solids separation process which was developed by GARD during 1968-1970 to concentrate and dewater dilute biological sludges.

In this original process the hydrophilic pumping properties of cellulose sponge were used in combination with a fine-pore plastic screen in much the same fashion as a vacuum filter, but without the high operating costs and power requirements of a vacuum pump. The operating principles of the screen and sponge filter are illustrated in Figure 2.

Sludges containing from 1%-3% solids are delivered to a horizontal moving screen filter. The moving filter consists of two layers: an upper layer of woven plastic filter screen, and a lower layer of cellulose sponge. The two layers move together over a support table where the sludge is deposited on the upper screen side. Liquids are drawn through the screen by the hydrophilic properties of the sponge, leaving the dewatered sludge containing 12%-18% solids on the screen belt. The sponge layer is then separated from the screen layer and the absorbed liquid squeezed from the sponge by a series of rollers.

The operating principles of the moving screen filter were used to design a laboratory scale waste treatment system. A laboratory system was fabricated, tested, and evaluated; this system operated at a waste feed rate of 1900 l/day, equivalent to a 14-man capacity.

Performance data from the laboratory systems were then used to design and size a full scale system capable of handling a nominal wastes feed rate of 2650 l/day, equivalent to a 20-man capacity. The full scale system was fabricated and evaluated in a series of tests over a three-month period.

System Design

Preliminary studies had indicated that the hydrophilic filter could be used to dewater raw sewage and that 90% reduction of suspended solids appeared feasible. It was expected that the filtrate could be further treated in carbon adsorption columns and a chlorination unit to achieve 90% reduction of BOD, and a reduction of coliform count to less than 240 MPN/100 ml. For testing purposes the nominal input levels of SS and BOD were assumed to average 750 mg/l.

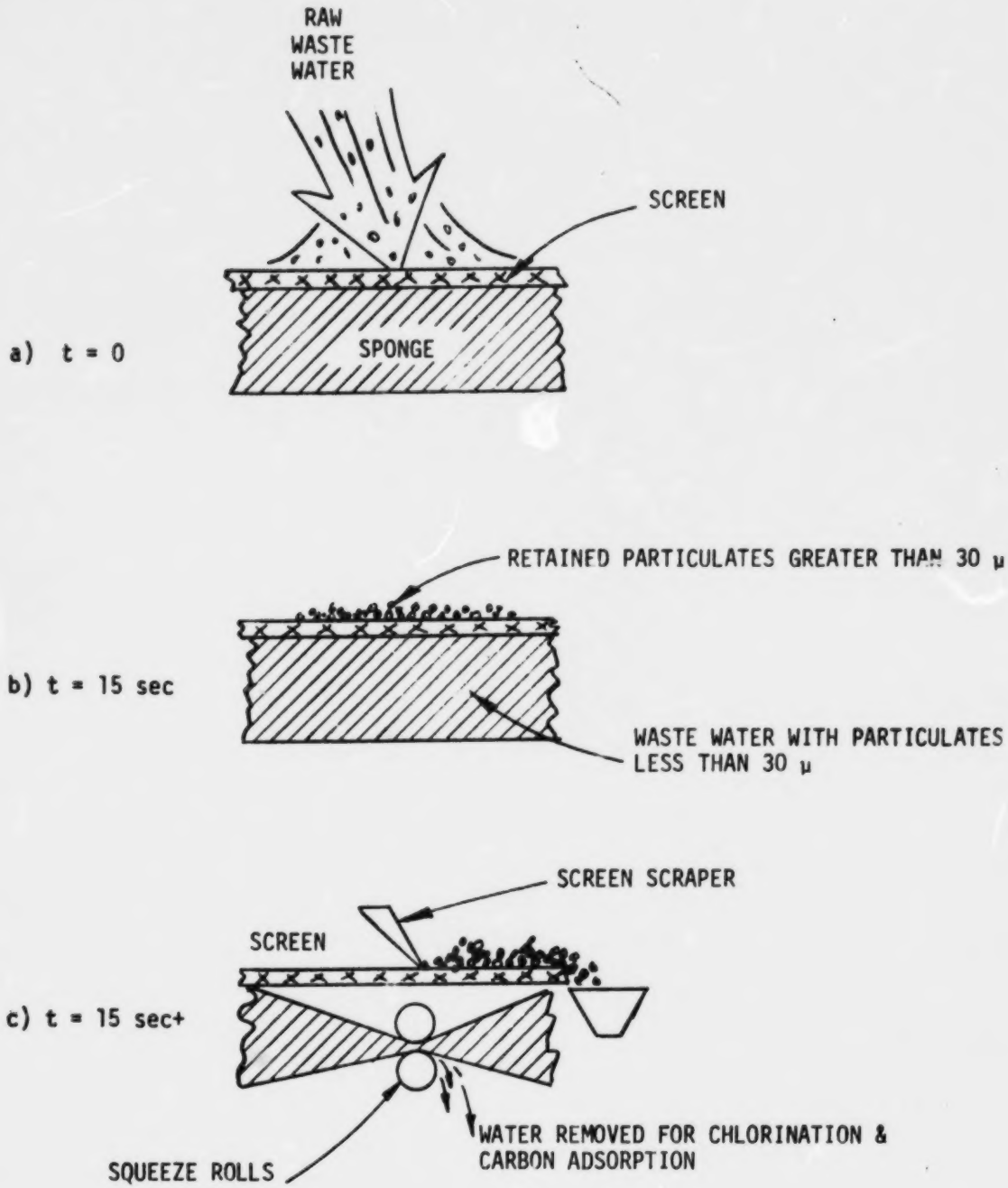


Figure 2 LIQUID SOLIDS SEPARATION

Filtration of Suspended Solids

In the basic system design it was recognized that efficient operation of the hydrophilic filter was the key element in the waste treatment system, since the filter alone would be required to remove the bulk of suspended solids from the waste stream. Ideally, the filter assembly would be capable of a high throughput and yet be compact, reliable, and simple to operate and service.

The filter screen material initially chosen was a readily available polypropylene fabric with a nominal ability to retain particles larger than 30 microns. This fabric had proven to be highly durable, with resistance to corrosive materials which might be present in the waste stream.

The hydrophilic sponge material which had been found to exhibit high water absorption characteristics was cellulose sponge. Another satisfactory material was urethane sponge which has better tear and abrasion resistance but somewhat less absorption capacity than cellulose.

The porosity of the screen material is such that water will not penetrate it unless drawn through by the hydrophilic action of the underlying sponge. Also, to achieve high filtration rates, the screen and sponge should remain in intimate contact during the dewatering step, and solids should be effectively removed from the screen after each cycle.

The ultimate efficiency of the filtration device is dependent upon the pore size of the screen and the particle size distribution of suspended solids in the influent sewage. Since the screen is capable of removing solids only larger than 30 microns, it is desirable to deliver wastes to the filter in a manner which preserves the largest particle size possible with prevailing transport piping. Tissue paper and solid kitchen wastes are not significantly affected during transport and are generally efficiently removed by the filter. However, operating tests demonstrated that mechanical action and attrition experienced during transport could reduce feces to particles in the 1-micron range which could easily pass through 30-micron openings in the filter screen. For this reason, the handling and delivery of the sanitary waste from the commodes to the filter became an important consideration in the overall solids removal efficiency of the complete system.

In most marine waste piping systems gravity drains would be anticipated as the normal method of transporting sanitary wastes to a treatment or collection site. Mechanical action and attrition could then be expected to be at a minimum in low velocity piping systems of this type, and would not seriously affect the particle size of the sanitary wastes.

Due to expected irregular input flow rates to the treatment system, a surge tank would be required to allow the waste to be fed to the filtration device at a relatively constant rate. A feed device which does not contribute to particle size reduction of the fecal material would also be required to realize the full potential of the filter.

In those cases where the particle size of the raw sewage is favorable, in the range above 30 microns in diameter, the hydrophilic filter alone will meet the required 90% removal efficiency for suspended solids. For operation where significant amounts of particles below 30 microns are present, it may be necessary to introduce a coagulant to the raw sewage to achieve the necessary solids reduction through this filter. In addition, if even more efficient removal of solids is required, a pressure filter can be included to remove the smaller size solids which pass the hydrophilic filter.

A series of comparison tests of commercially available gravity and pressure bed filters indicated the pressure type filter as the more effective for removal of suspended solids in the range below 30 microns. The performance of the pressure filter was highly satisfactory, but was shown to be dependent upon the incoming suspended solids level remaining below 250 mg/l. In addition, bacteriological growth in the pressure filter media which sometimes occurred would cause agglomeration of the media and eventual plugging; this indicated a need for inhibiting growth within the filter bed by chemical treatment or other means.

In the normal mode of downflow operation the pressure filter would remove the finer size particles and drop the influent suspended solids level from the 150-250 mg/l range to an effluent level of 40-100 mg/l. Above an influent level of 250 mg/l the pressure filter would tend to plug in about one-third or one-fourth of the normal four-hour cycle and thus require excessively frequent cleaning by back-flushing.

Removal of Solubles and Reduction of BOD

The total filtering and adsorption system was operated and shown to be effective for removing dissolved solids and reducing BOD levels. Operating data accumulated on the system was not sufficient to accurately predict duration performance for field conditions, but BOD reductions in excess of 90% were achieved in several series of individual tests, which lasted for two to six hours each. The average reduction in BOD over the total test program was approximately 80%, but this average included operation during periods when excessive amounts of suspended solids passed into the carbon columns, causing plugging and disturbance of flow in these columns.

The primary factors governing carbon column performance were the entering suspended solids concentration and the velocity and direction of flow in the column. Removal of dissolved organics in the carbon columns was effective in the upflow direction at 164 l/m^2 when the entering suspended solids level was below 100 mg/l. In downflow the carbon bed removed particulates and eventually became plugged after several days of operation. In upflow the bed still removed some particulates, but to a significantly lesser extent, and operated properly for over ten days of intermittent use without plugging.

In the final system a series of six carbon beds with a total bed volume of 0.135 cubic meters were required to meet the specified dissolved solids and BOD reductions of 90%. The carbon beds were designed to operate in upflow at 205 liters per minute per square meter, and at a retention time of approximately 15 minutes for a feed rate of 3.8 liters per minute.

Reduction of Coliform Content

Treatment to lower the coliform content of effluent from the carbon bed entailed chlorination. Addition of a liquid solution of sodium hypochlorite required a liquid feed system, controls, and a holding tank but appeared to be effective in achieving coliform reduction.

An alternate system consisting of a holding basket containing solid tablets of calcium hypochlorite and a syphon-fed dwell chamber, also proved highly effective in properly reducing the coliform level. This system operated with no moving parts, since the syphon automatically drew liquid through the contact basket and discharged it after filling the dwell chamber. The solid tablets and syphon configuration were shown to be the preferred subsystem for use in the total waste treatment system.

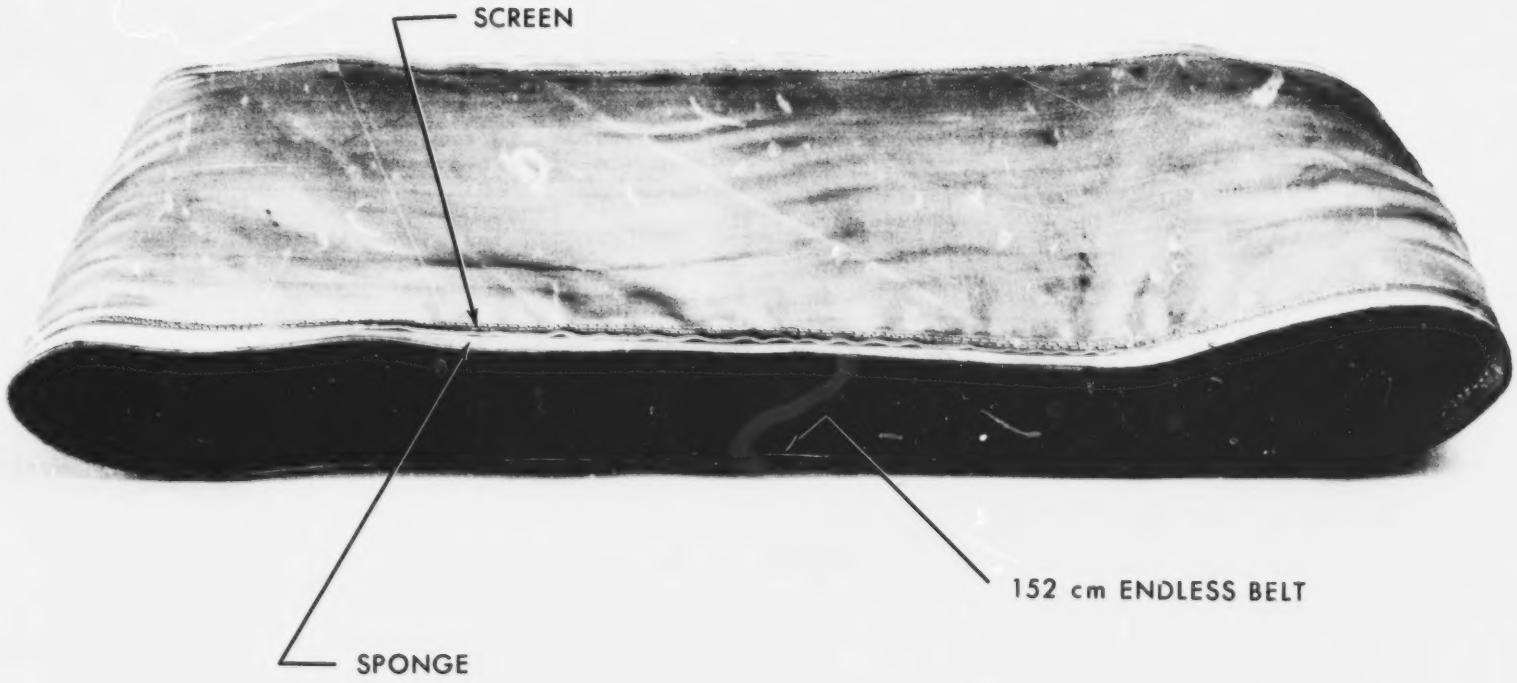
Laboratory System

At the beginning of the program, major emphasis was placed upon developing a waste treatment system suitable for shipboard operation. Previous design and performance data from the proprietary sludge dewatering system were the basis for design and fabrication of a laboratory prototype filtration system which could be used to evaluate concepts for a full scale shipboard unit.

Screen Filter

In the initial laboratory prototype filter assembly, both the filter screen and cellulose sponge were permanently attached to a 23-cm wide by 152-cm long endless belt, as shown in Figure 3. The complete filter assembly consisted of a wastes metering pump, feed distribution flume, screen and sponge belt, solids removal scraper, and wringer rolls. The equipment arrangment is shown in Figure 4. A variable speed tubing pump was used as the wastes metering pump. Although this pump operated with an unobstructed 1.6-cm diameter pumping tube, it was necessary to macerate all waste in a kitchen waste disposal unit before it could be conveniently pumped to the filter assembly.

The feed wastes were distributed across the width of the belt by a diverging flume, but prevented from overflowing the belt edges by the extended outer blade pressed against the moving screen at the drive roller. The absorbed water was removed from the sponge by passing the screen-sponge belt assembly through a pair of spring-loaded wringer rolls.


SCREEN
SPONGE
152 cm ENDLESS BELT

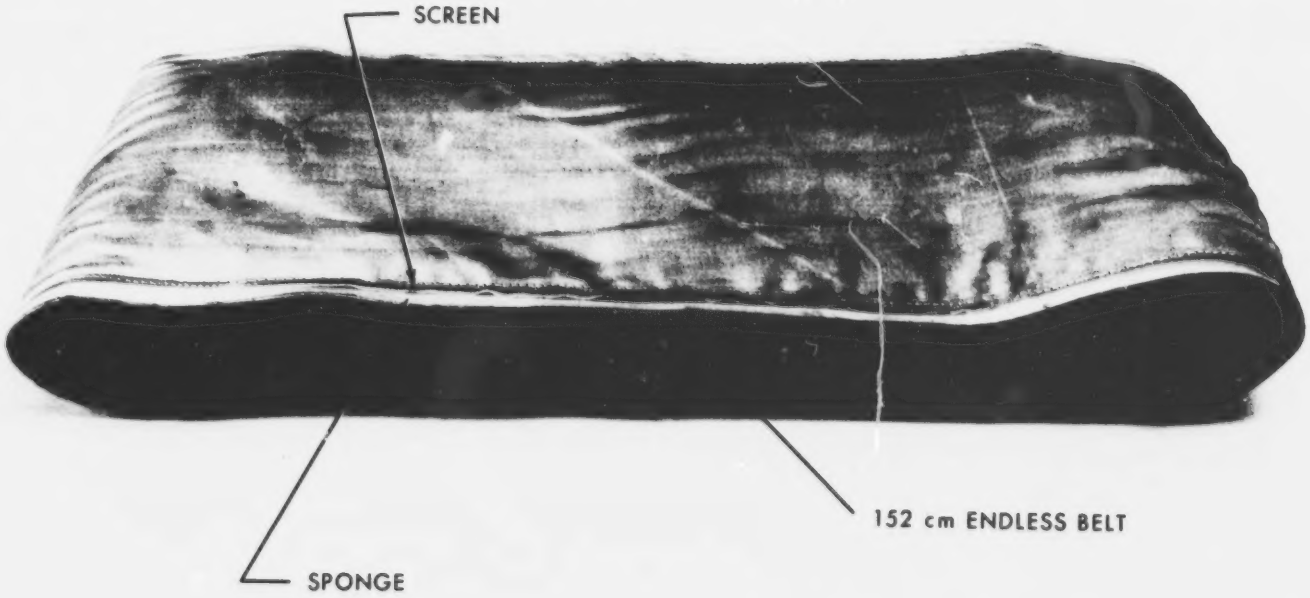


Figure 3 LABORATORY SYSTEM SINGLE-BELT SPONGE AND SCREEN

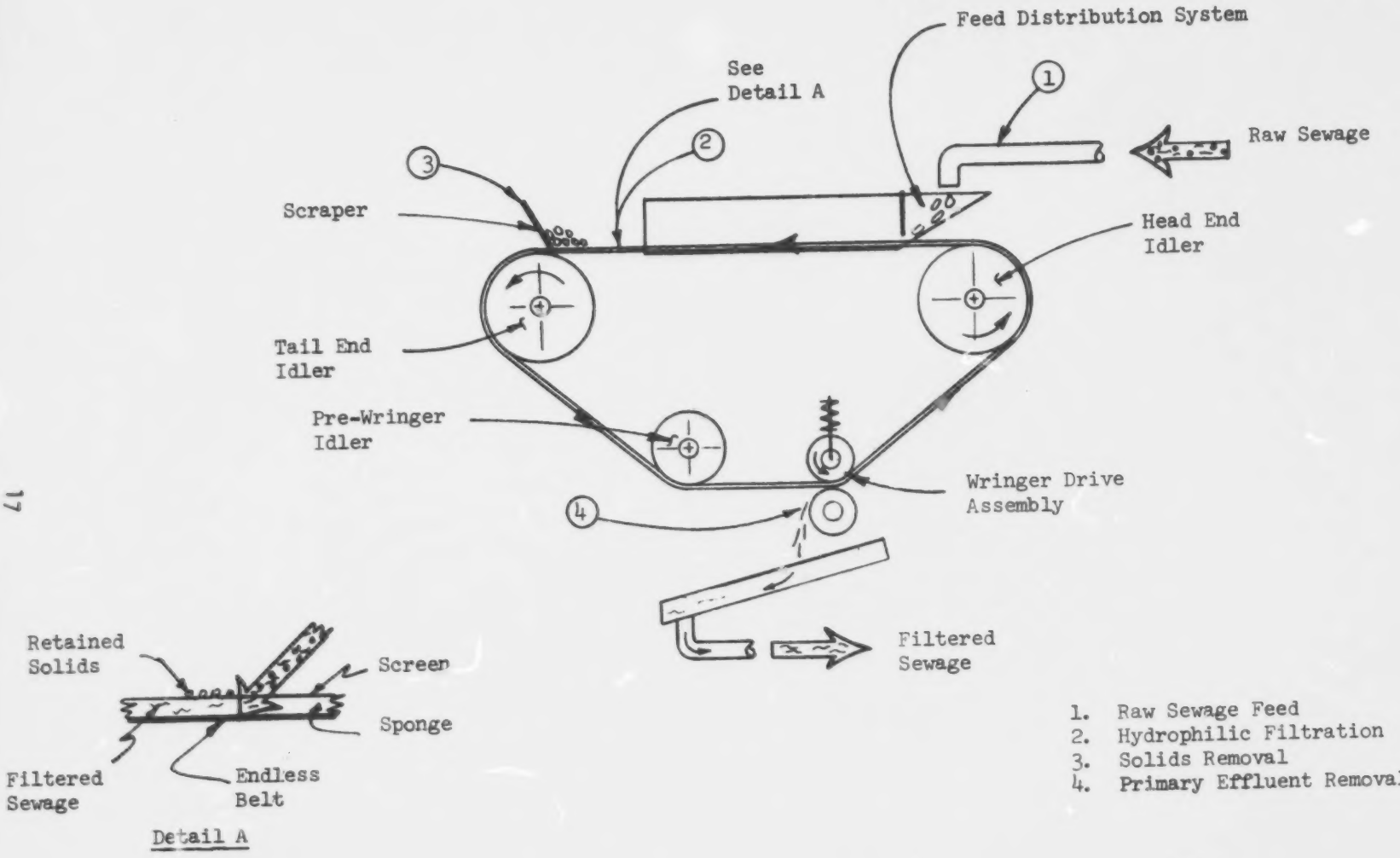


Figure 4 LABORATORY PROTOTYPE FILTER EQUIPMENT ARRANGEMENT

Although the macerated wastes used in the early laboratory tests contained both sanitary wastes and kitchen food-scrap materials, the solids retained by the filter-screen were predominantly the vegetable matter used to simulate the kitchen wastes. It was not possible to accurately determine the relative efficiency of the filter for the various sewage components, but it appeared qualitatively that the filter was removing practically all of the solids exclusive of the fecal matter. Based on visual estimation the filter efficiency for the highly macerated fecal matter appeared to be low, probably less than 10%, but over 90% for the other wastes solids.

Based on these observations, it was expected that a significant increase in filter efficiency would be achieved when unmacerated raw sanitary waste could be applied to the filter. Maceration of all solids did produce a more uniform sewage than could otherwise be obtained, which was important in evaluating the day-to-day performance of system components.

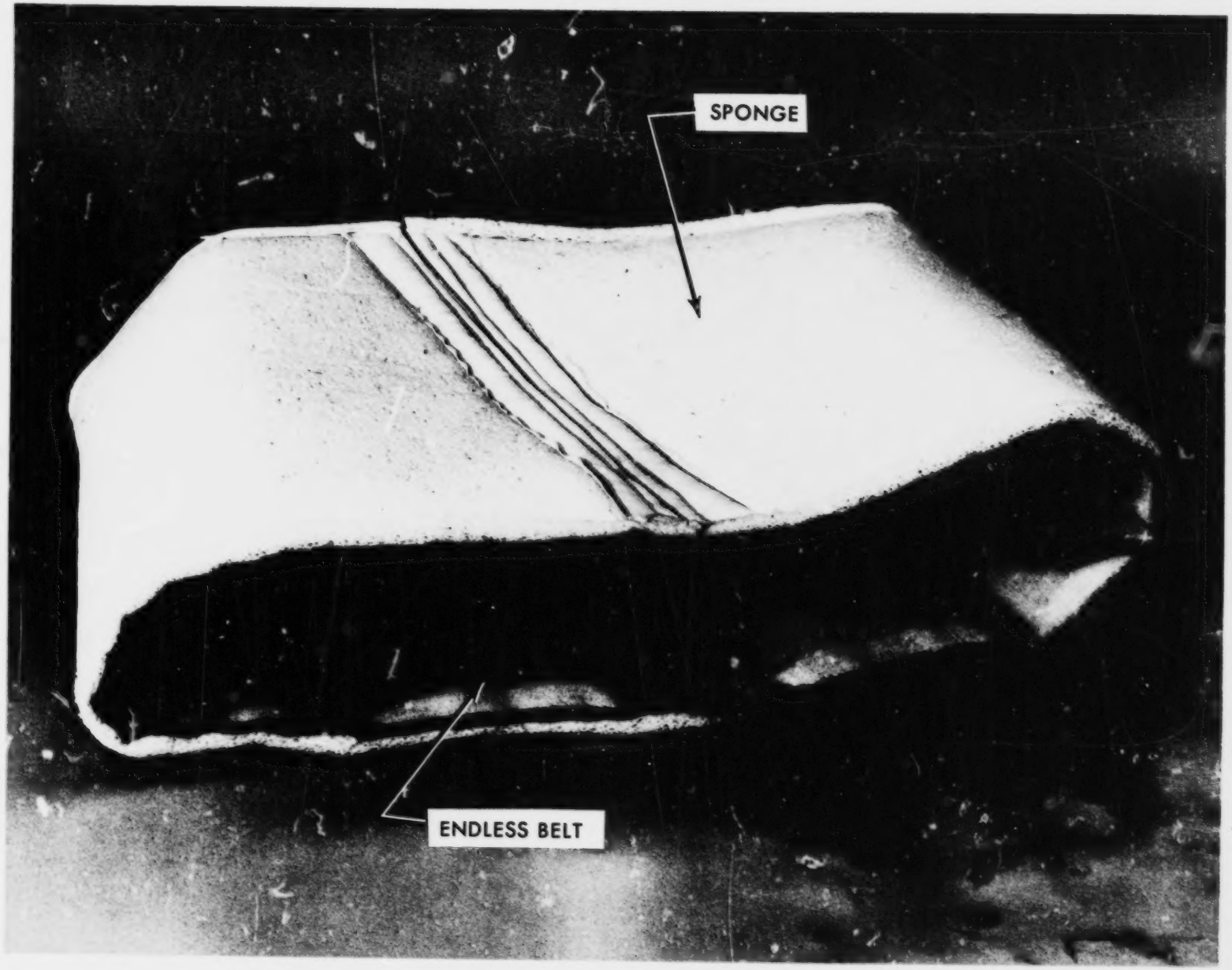
Preliminary tests also indicated that grease in the raw sewage could not be effectively removed from the belt by scraping alone; the residual grease tended to blind the screen and greatly reduce the filter rate. Further tests indicated that the grease could be removed by water sprays.

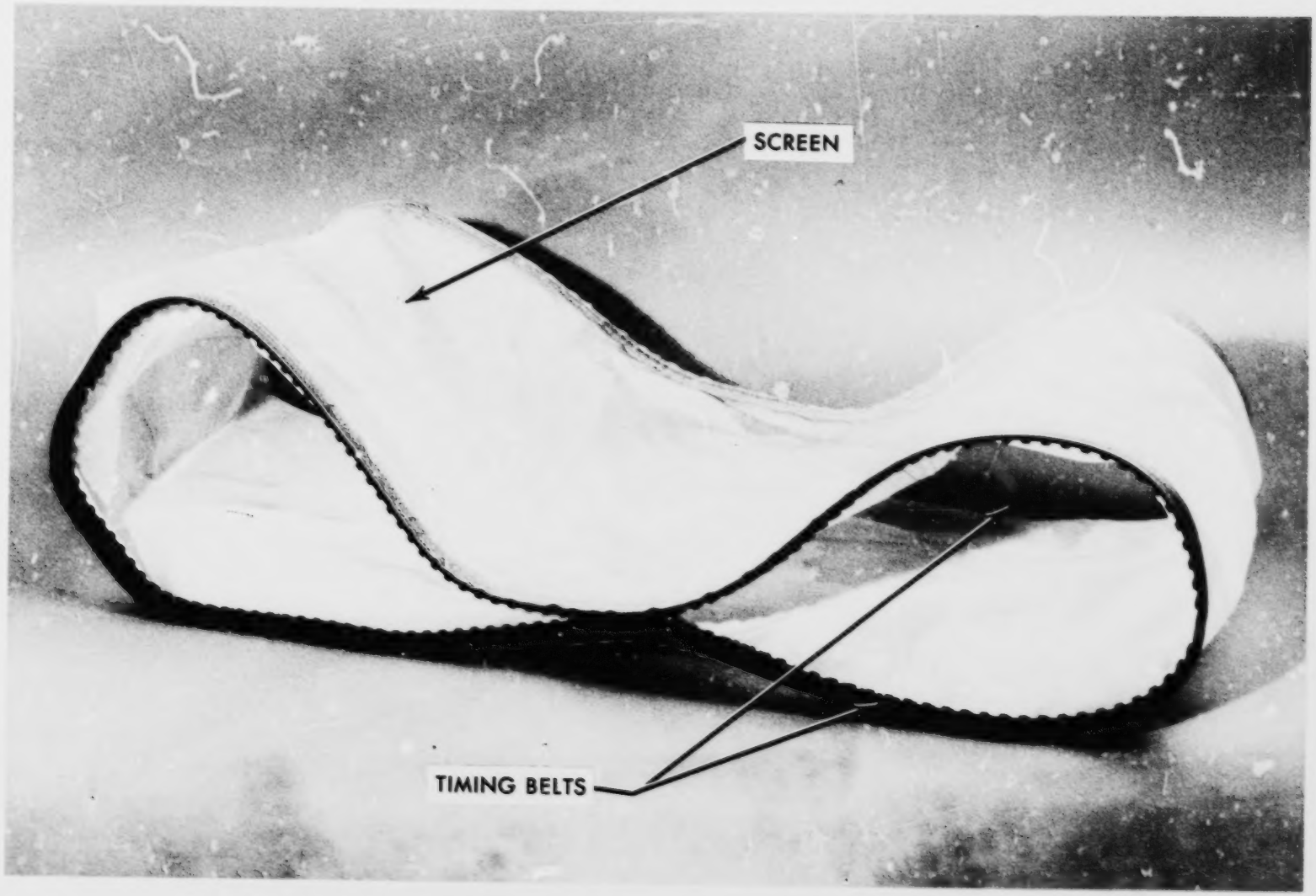
At this time, it was decided to change the single belt system to a two-belt arrangement in which the screen would be separated from the sponge after the dewatering step to allow the screen to be thorougly cleaned by water sprays before returning to the raw wastes feed position. In the dual belt system the sponge was again permanently attached to an endless belt, as shown in Figure 5a, to provide support and a means for moving the sponge. A separate filter screen belt was fabricated by attaching the edges of the screen material to two timing belts as shown in Figure 5b. The dual belts and drive assemblies are shown in Figure 6.

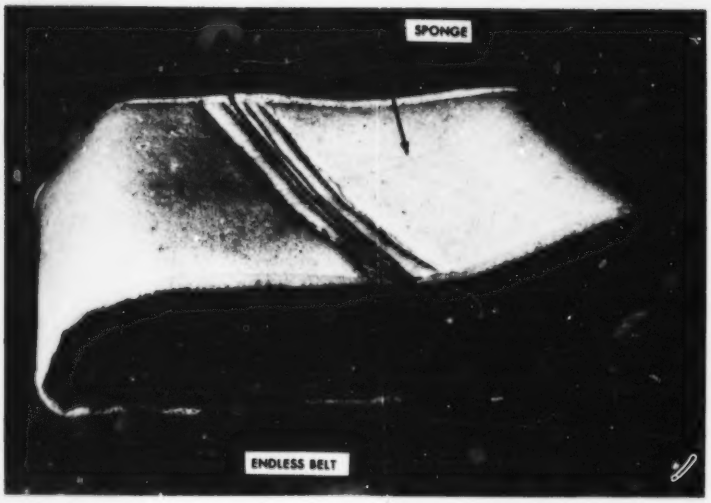
After the liquid was drawn through the screen by the sponge, the sponge belt separated from the screen and passed through the wringer rolls to remove filtered liquid. The filter belt passed under the rubber scraper blade to remove solids, and then passed through an array of water spray nozzles to remove lightly embedded particles.

Operation of the dual belt filter in this manner successfully indicated that blinding of the screen could be eliminated by continuous water spray cleaning after scraping. A filtering rate of 3.8 liters per minute with a filter belt 23 cm wide could be maintained at a belt speed of 5 cm per second. At this belt speed the residence time for the dewatering step was approximately 6 seconds; this time was adequate for the water deposited on the screen to be drawn through the screen by the sponge.

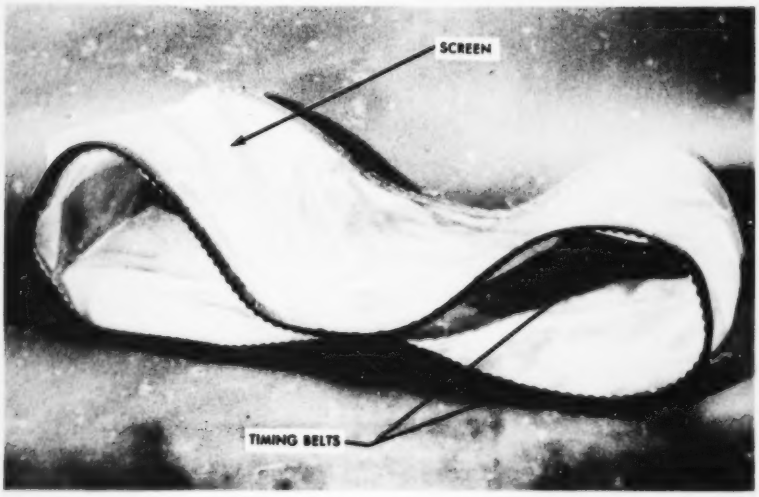
After blinding of the screen was controlled by using water sprays, a carbon bed was added to the laboratory system for the removal of dissolved solids. However, after several tests with macerated mixtures of kitchen wastes and feces, the carbon bed became plugged by fine suspended solids under 35 microns which passed through the moving screen filter. Since a finer porosity screen could not be obtained which could be readily cleaned after each filtering cycle, bed filters were investigated as a supplementary measure for removing fine suspended solids.


SPONGE
ENDLESS BELT


SCREEN
TIMING BELTS

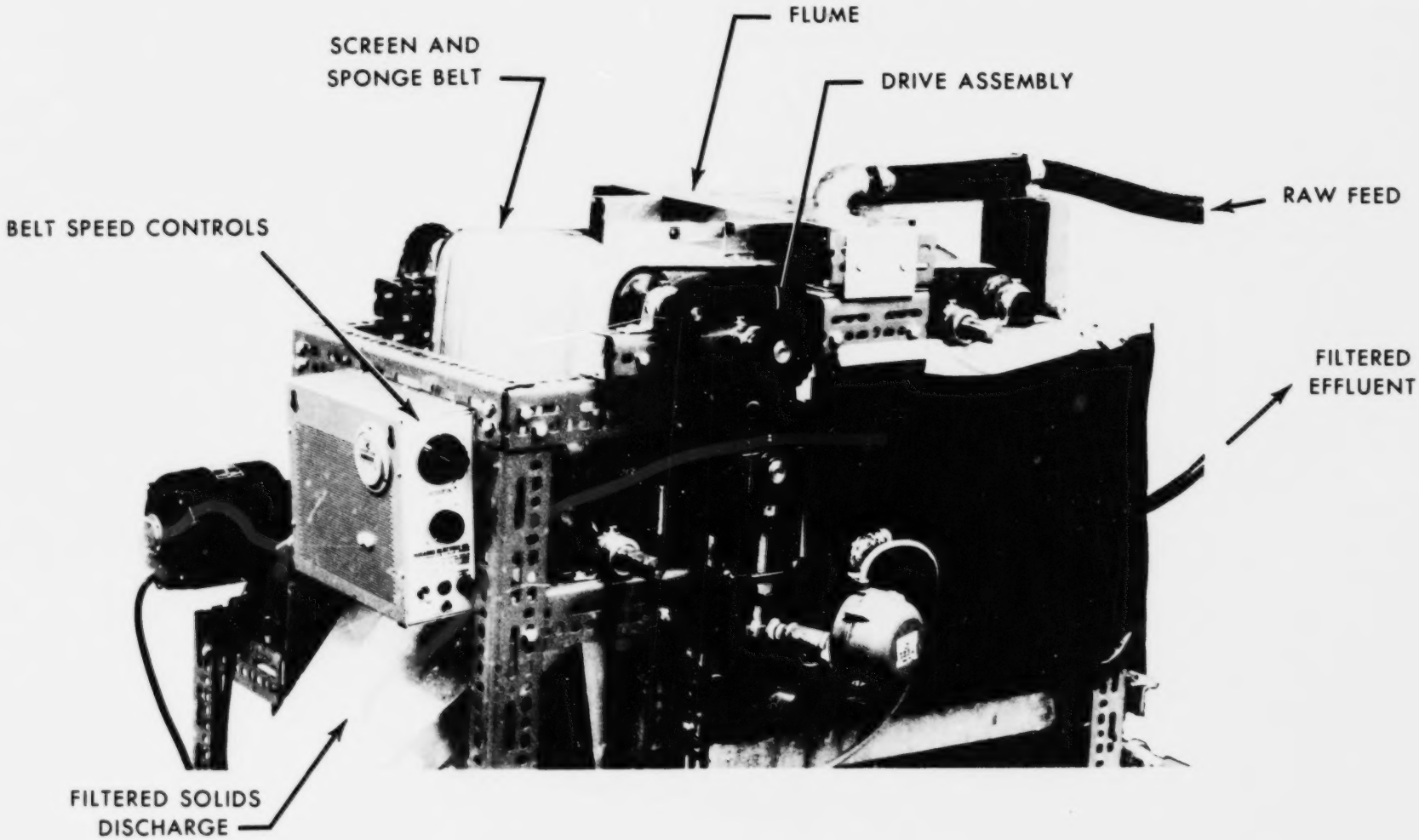


5A SPONGE BELT



5B FILTER SCREEN BELT

Figure 5 FILTER BELTS


FLUME
SCREEN AND
SPONGE BELT
DRIVE ASSEMBLY
RAW FEED
BELT SPEED CONTROLS
FILTERED
EFFLUENT
FILTERED SOLIDS
DISCHARGE

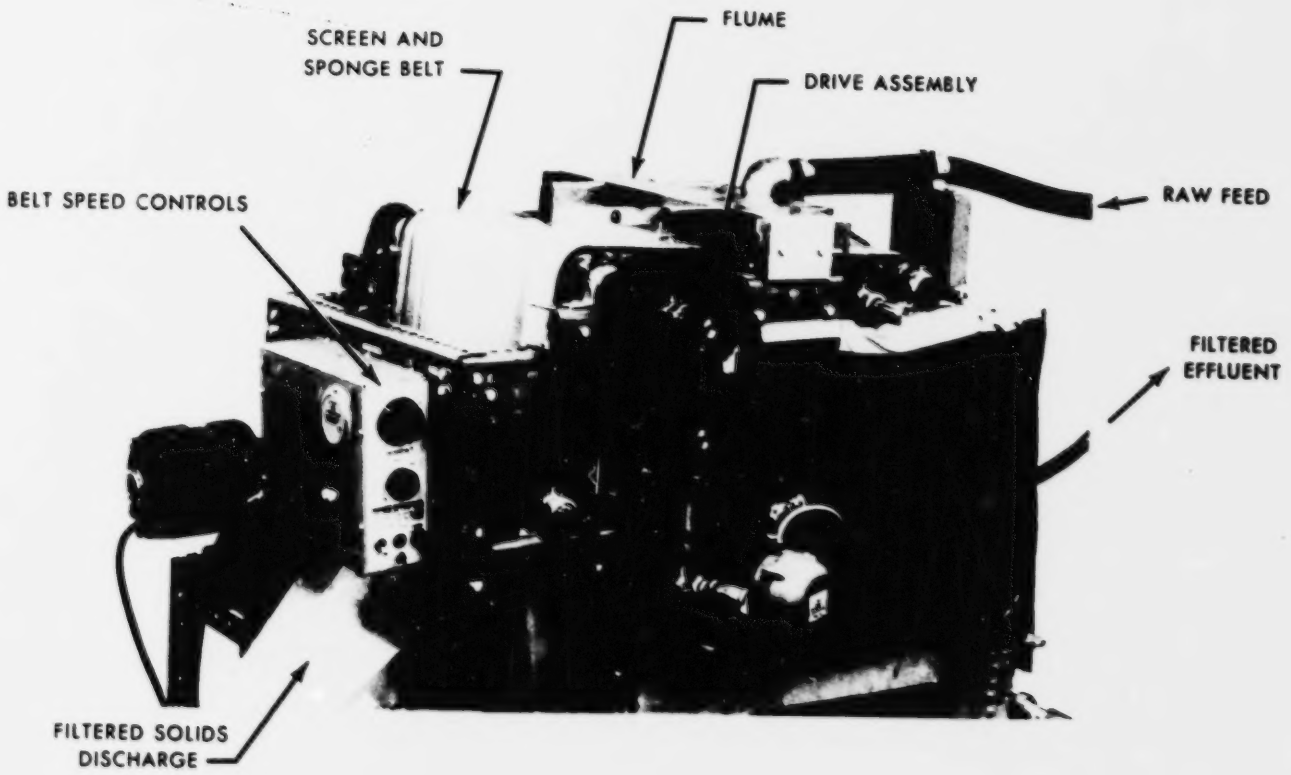


Figure 6 DUAL-BELT SYSTEM AND DRIVE ASSEMBLY

Two types of filters were investigated: (1) gravity bed, and (2) pressure bed filters. In a series of tests each type was installed after the MSF to treat effluent from the filter screen. In the gravity filter, gravel and anthracite were used as the media, while in the pressure filter slightly compressible polystyrene granules were used.

The pressure bed succeeded in lowering the suspended solids from the 150-250 mg/l level to the 60-100 mg/l level, while the gravity bed lowered suspended solids to only 185-200 mg/l. On the basis of this performance the pressure filter was selected for evaluation as a component in the wastes treatment system. In the pressure filter the polymer selected was polystyrene in the form of resin granules, 0.30-0.42 mm in diameter. The filter was operated in the downflow configuration with the filter media supported on a stainless steel screen. The unique feature of this filter was the method used to backwash the filter media.

The specific gravity of the media is only slightly greater than that of water; when flow is reversed from downflow to upflow, the media easily becomes fluidized. The operation of the filter is illustrated in Figure 7. In the normal mode, 7-A, of filtering the feed pump delivers filtrate from the MSF at a constant volume to the top inlet of the pressure filter unit. After passing down through the filter media, the cleaned filtrates exits at the bottom outlet.

To backwash the filter a separate backwash pump is employed. The valves are arranged as in 7-B to reverse the flow through the filter. This reversal of flow fluidizes the media which is then permitted to circulate in this closed loop for several minutes. The violent action experienced when the slurried media passes through the centrifugal backwash pump separates the particulates from the media grains.

The particulates are then discharged through a special wire-wound septum with flow entering from filtrate storage, and particulates exiting to solids storage as shown in 7-C. The wedgewire septum will not pass the media granules but will permit the smaller particulates to pass from the system.

After solid particulates are discharged, the filter bed is reset in place, with the flow as indicated in 7-D, and then put back on stream with flow once more as shown in 7-A.

Preliminary tests on the pressure filter unit indicated that it would remove approximately 70% of the suspended solids present in the MSF effluent. On the basis of this performance it was decided to include a pressure filtration unit in the full scale treatment sytem. When this filter is not required to meet effluent standards, it can be easily bypassed. The carbon adsorption columns then would treat the effluent directly from the MSF unit.

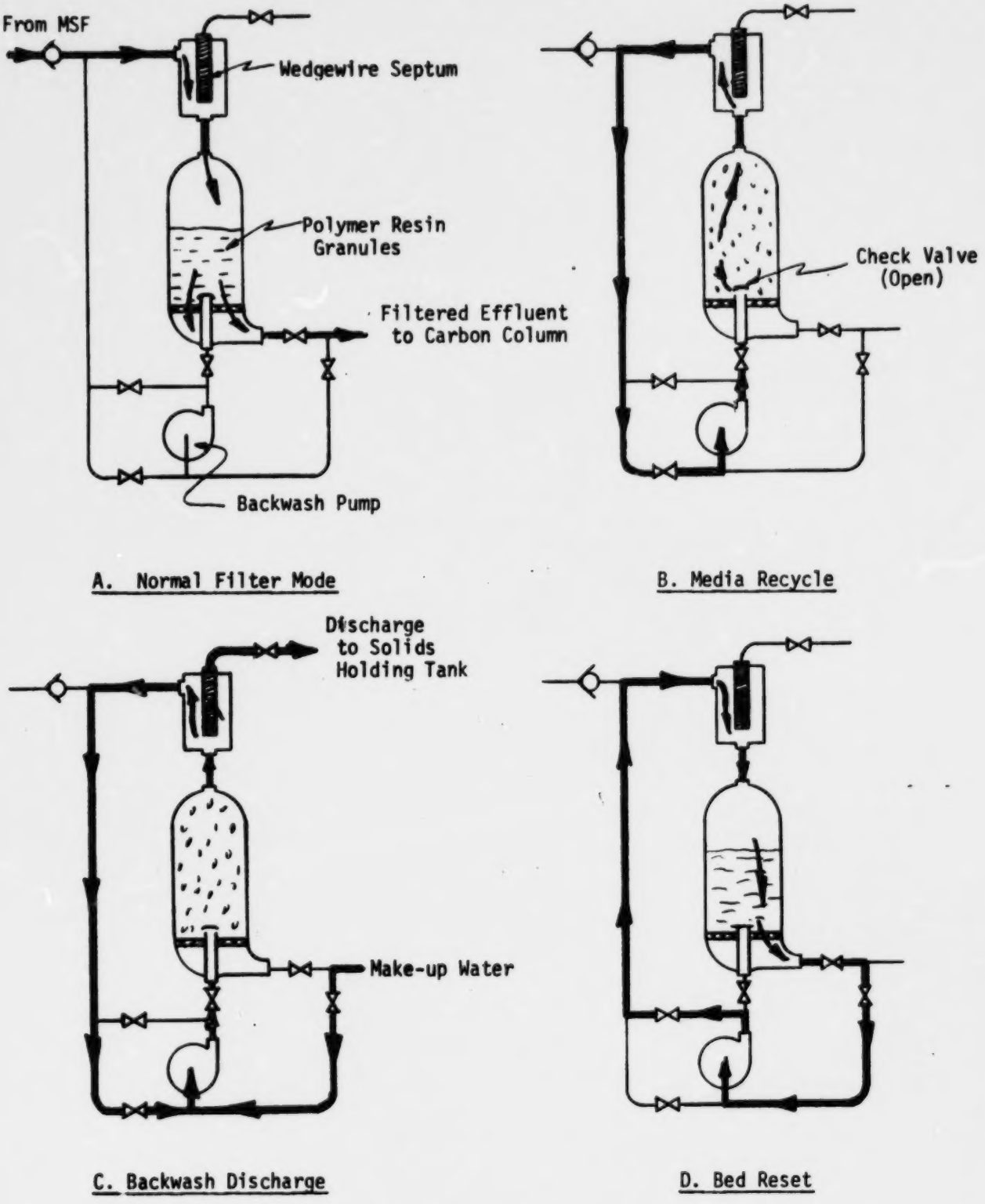


Figure 7 PRESSURE BED FILTER OPERATION

Carbon Beds

The initial carbon adsorption beds tested as part of the laboratory system were simple carbon columns arranged in a downflow configuration. Each column was 15 cm in diameter and approximately 75 cm deep. The adsorbent material was activated carbon granules, 0.55 to 0.65 mm in diameter, supported on a 10-cm layer of 3-6 mm gravel. It was expected initially that although some particulates would remain in the bed, the liquid throughput rate needed could be maintained during the expected useful life of the bed material without excessive increase in pressure drop across the bed.

During early tests, it was discovered that oils, grease, and fine particulates which passed the MSF were capable of plugging the carbon bed within several days, causing pressure drop to increase from 0.07 atm to over 0.68 atm. The size of the carbon granules was increased to 0.8-0.9 mm, but plugging problems continued.

In an effort to reduce plugging of the carbon bed, the flow was reversed to upflow and the granular size was returned to the original 0.55-0.61 mm size. The purpose was to expand the bed material and allow particulates to pass through the adsorbent. Laboratory tests confirmed that the expanded bed would pass the particulates in the influent, but only if the suspended solids level was below 100 mg/l before entering the carbon columns.

After the pressure filter was included as part of the filtering process, the inlet suspended solids level to the carbon beds remained below 100 mg/l. During these tests the two carbon beds in series operated to produce outlet BOD levels below 100 mg/l and the total system operated with equal to or greater than 90% overall reduction of BOD.

Chlorination Assembly

The chlorination assembly used during laboratory tests consisted of a chemical feed pump and a 60-liter contact tank. The tank was baffled to create an extended flow path and provide a stay-time approximating fifteen minutes at a nominal effluent flow rate of 4 liters per minute.

Common laundry bleach containing 5.25% chlorine was metered into the contact tank at a flow rate of 3 ml per minute. This flow rate was held fairly constant, and the metering pump was operated during selected tests when the overall system was operating properly. At this flow the chlorine concentration in the effluent entering the contact tank approximated 50 mg/l. When operating in this manner the exiting chlorine residual concentration ranged from 0.5 to 2.0 mg/l based on standard orthotolidine testing procedures during operations with varying feed compositions and system component arrangements.

Full Scale System

Based upon results obtained with the prototype system, a full scale system capable of processing 2650 liters of wastes/day was designed, fabricated, and tested under simulated shipboard conditions. A discussion of final hardware design is presented to aid in understanding the performance of the waste treatment system reported in Section V.

The major components in the full scale system were the feed tank, feeder valve, moving screen filter (MSF), pressure filter, carbon beds, chlorination unit, intermediate effluent tanks, pumps, valves, and electric l contacts. The system is shown in Figure 8.

In the development of shipboard treatment system major emphasis was placed upon keeping the system as simple as performance requirements would permit. The mechanical operation of the major components in the treatment system is also described in relation to performance objectives.

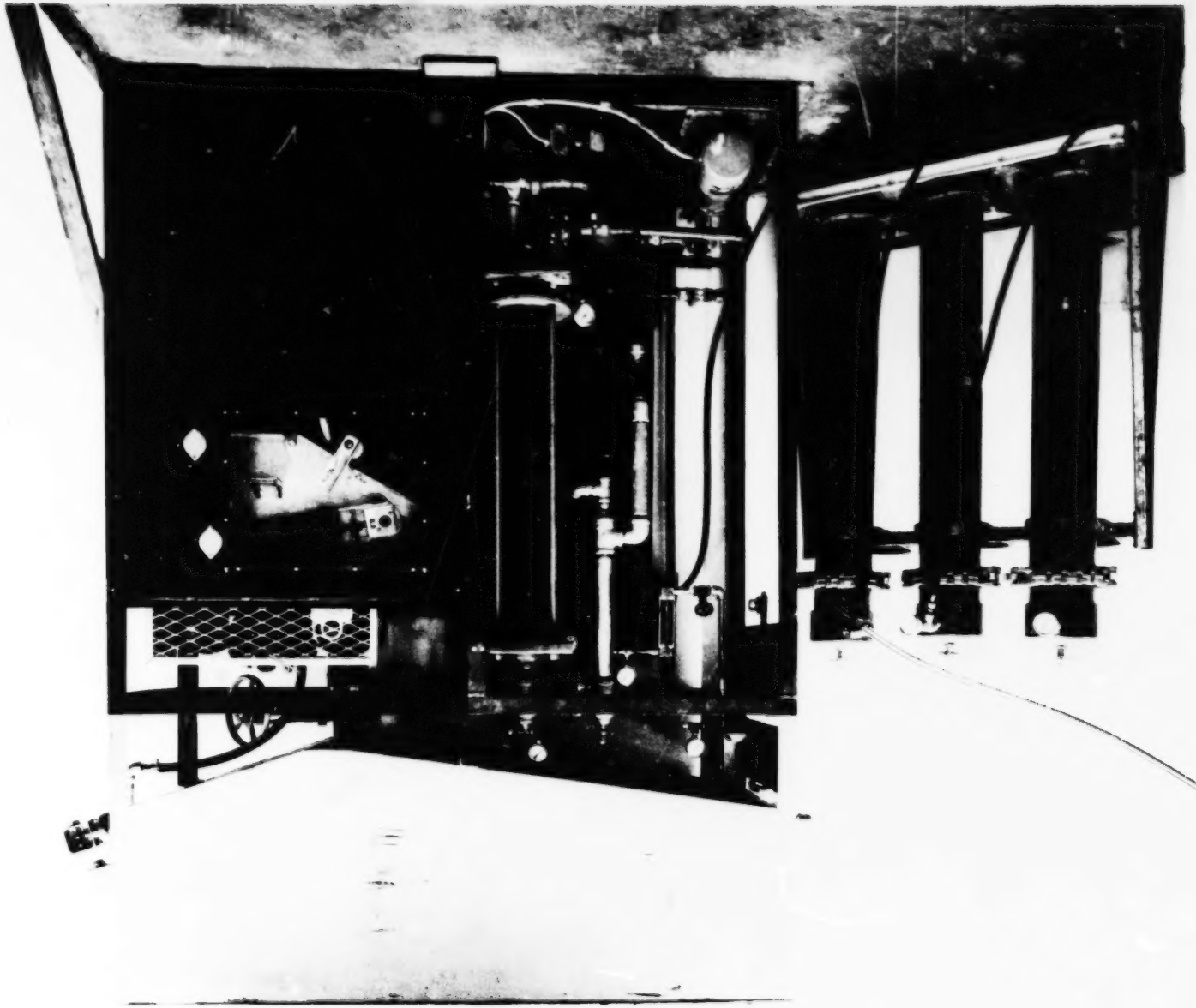
Feed Tank

In the original design concept, all wastes, namely sanitary, galley, laundry, wash basin, and showers were to be directed to a single feed tank from which they would be transferred by gravity flow directly to the MSF assembly. After reviewing the expected water usage rate for a 15-man vessel, it was decided that for a treatment system with a nominal throughput of 4 liters per minute, an 800-liter feed tank would be required to handle surge conditions.

In specifying the original design limitations on the system size, a maximum height of 2.8 meters and a maximum width of 73 cm was established for the total system. Based on additional design considerations the space allocation for the feed tank height was limited to 76 cm as shown in Figure 9.

The tank was fabricated from 12-gauge steel and coated with a coaltar epoxy liner. The level controllers which start and stop the overall filtering process are mounted on the side of the tank. These controllers are large-diameter diaphragm-operated snap-action switches as shown in Figure 10. The shut-off valve at the tank outlet is a manually-operated knife-gate valve.

The coaltar liner appeared to be entirely suitable for this application. The level controls gave reliable service and did not malfunction during the test program. The knife gate valve does not offer any flow restrictions in the wide open position and readily passed solids up to 8 cm in diameter. The shallow 20° slope of the tank bottom allowed some solids to accumulate and would not be acceptable for shipboard installation. Tanks receiving sanitary waste will require a minimum slope of 30°. Since the majority of the solids will be from the sanitary and galley drains, it would be desirable to segregate this sewage in a separate tank for immediate processing by the MSF device. This smaller tank should be located to permit gravity flow to the MSF and minimized disturbance of solids as in the original system arrangement. A second tank



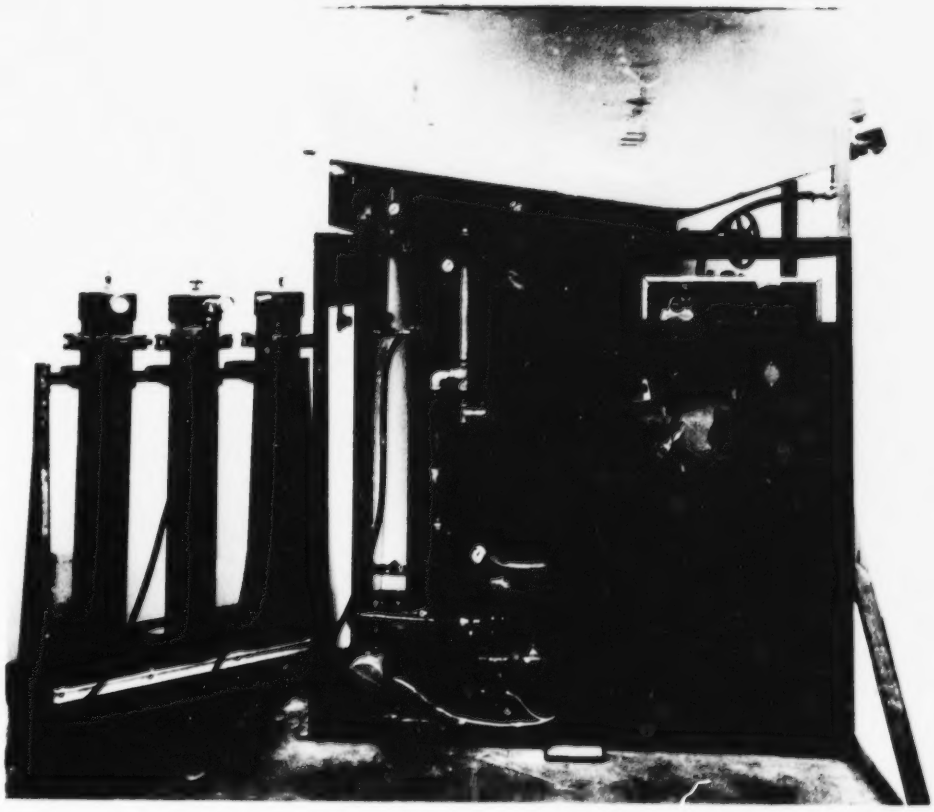


Figure 8 FULL SCALE MSF WASTE TREATMENT SYSTEM

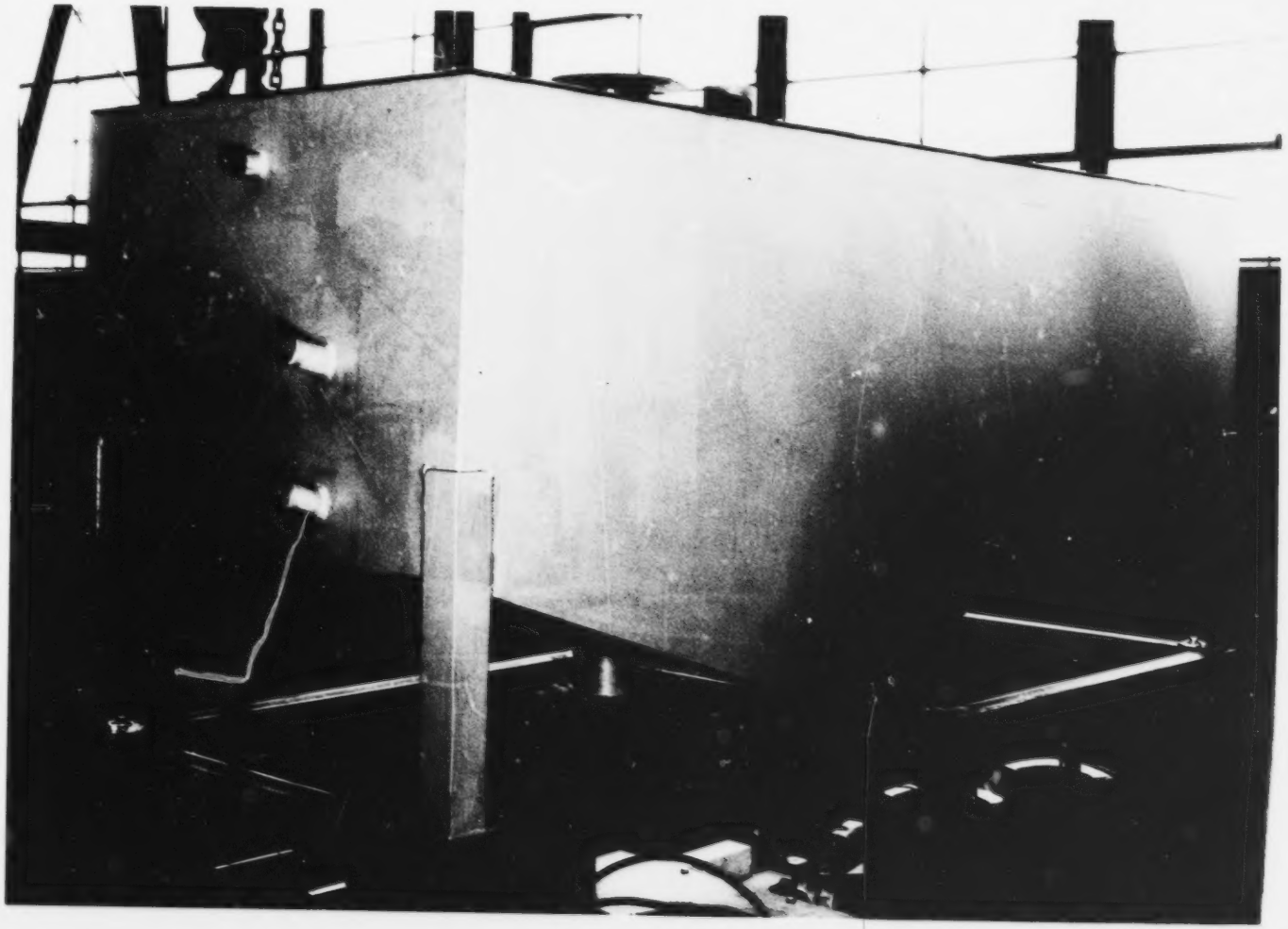
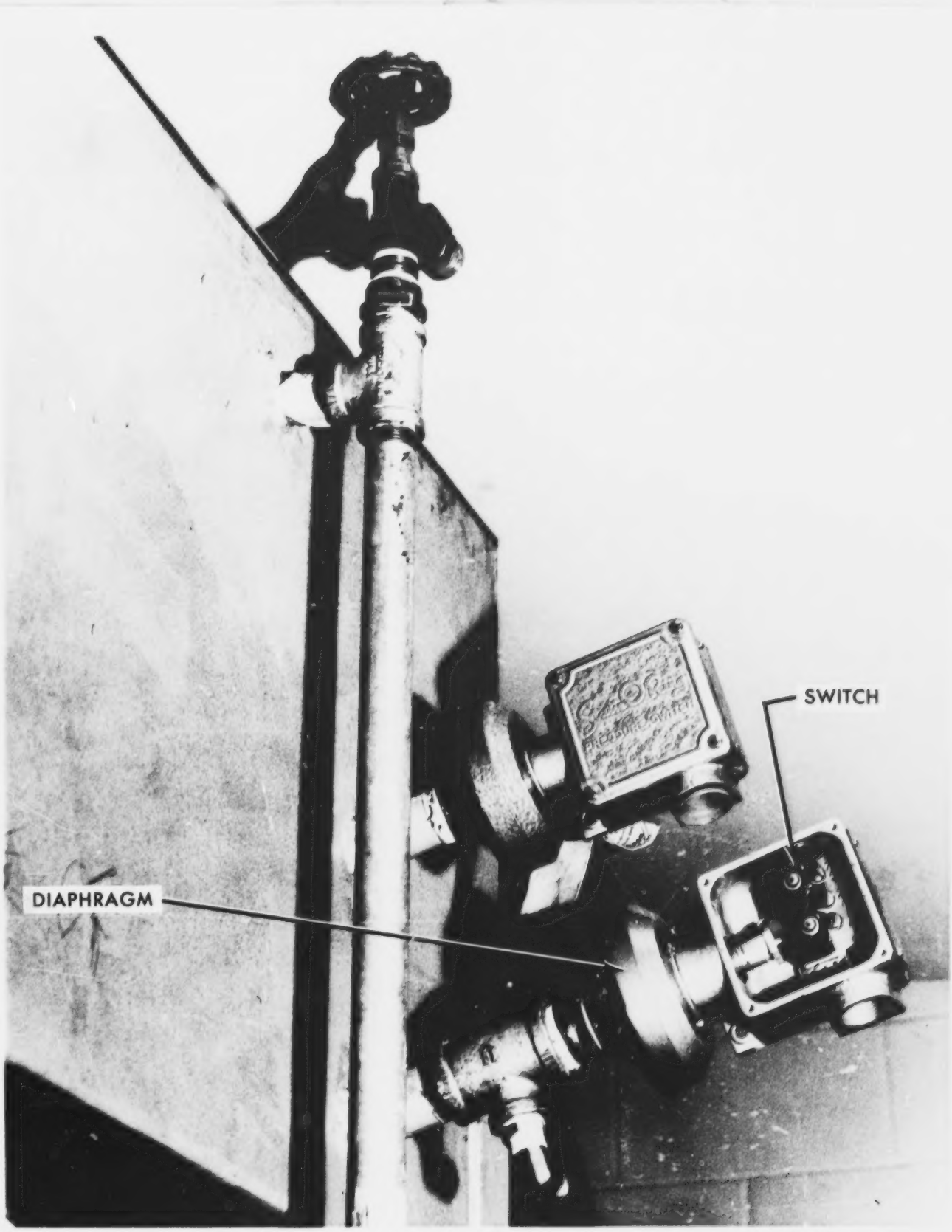


Figure 9 MAIN FEED TANK


SWITCH
DIAPHRAGM

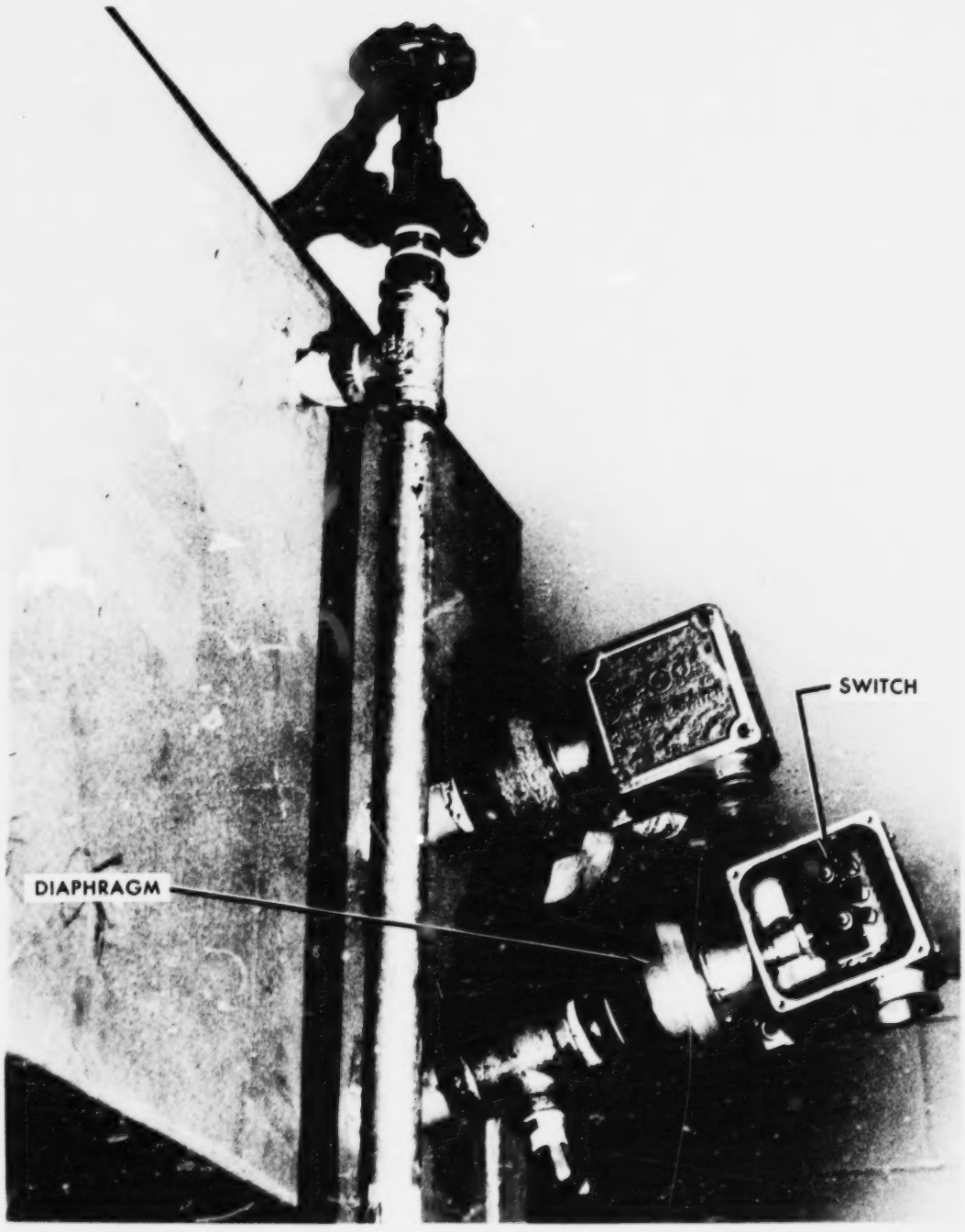


Figure 10 FEED TANK LEVEL CONTROLS

would be required for laundry, wash basins and shower water, but since the amount of solids in these streams would be minimal, these wastes could be pumped directly to the MSF with little effect on the solids size and filterability of these wastes.

Feeder Valve

To achieve the necessary metered feed to the moving screen filter, a single cavity rotary feeder was designed and fabricated as shown in Figure 11. The valve is connected directly to the bottom of the inlet feed tank. Wastes from the feed tank enter the rotating cavity and are discharged directly to the MSF. The feeder valve will transfer solids up to 5 cm in diameter without any appreciable disintegration of the solids. As wastes are discharged, the cavity fills with air, which is admitted to the feed tank during the next cycle. This aeration effect tends to maintain the raw sewage in an aerobic condition.

The body of the feeder is stainless steel and the rotating cavity is bearing bronze. The feeder valve is chain driven through a slip clutch from the main drive motor, which also drives the moving screen filter and sponge belts. The single cavity rotary feeder was initially designed with a PVC rotor which became badly scored after approximately 60 hours of operation. A replacement rotor fabricated from bearing bronze was then installed; the bronze rotor operated satisfactorily for over 100 hours of operation.

In general, the feeder performed well but occasional blockage occurred due to accumulation of paper which remained in the feed tank until the tank completely emptied. It is expected that this problem will be minimized or eliminated if the bottom slope of the feed tank is increased to the recommended 30° minimum.

The rotary feeder is driven through a slip clutch which protects the motor if the feeder jams. When the clutch disengages, the movement of the driven face plate can be detected by a limit switch to signal that an overload has occurred. To clear the jam it is necessary to clear the feeder valve by manually rotating the feeder in the reverse direction.

Moving Screen Filter (MSF)

The design of the full size MSF was based upon criteria developed during testing of the laboratory prototype device. The full size unit is approximately 75 cm long, 50 cm high, and 70 cm wide. All internal components of the MSF are constructed of stainless steel, plastic, and rubber to resist the corrosive effects of the sewage. The nominal capacity of the unit is 4 liters per minute at a belt speed of 4 cm per second. The MSF assembly is shown in Figure 12.

The wastes discharged from the rotary feeder fall directly upon the filter screen and are contained on three sides by vertical sides of a sewage retainer pressing against the screen. The screen and sponge are positioned on an incline to prevent the sewage from overflowing the open end of the retainer.

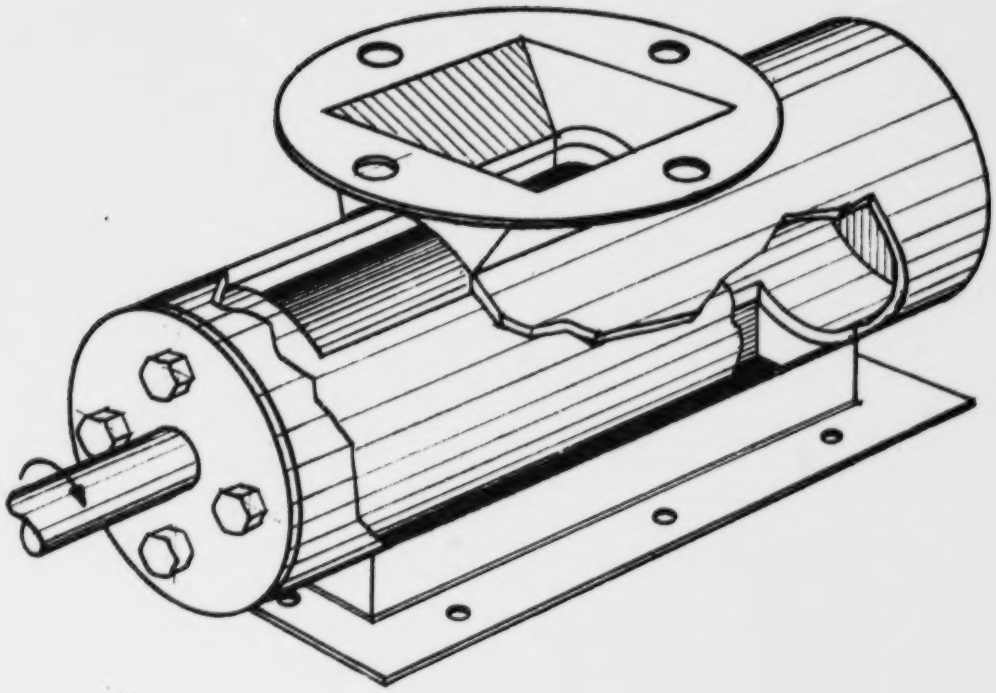


Figure 11 ROTARY FEEDER VALVE

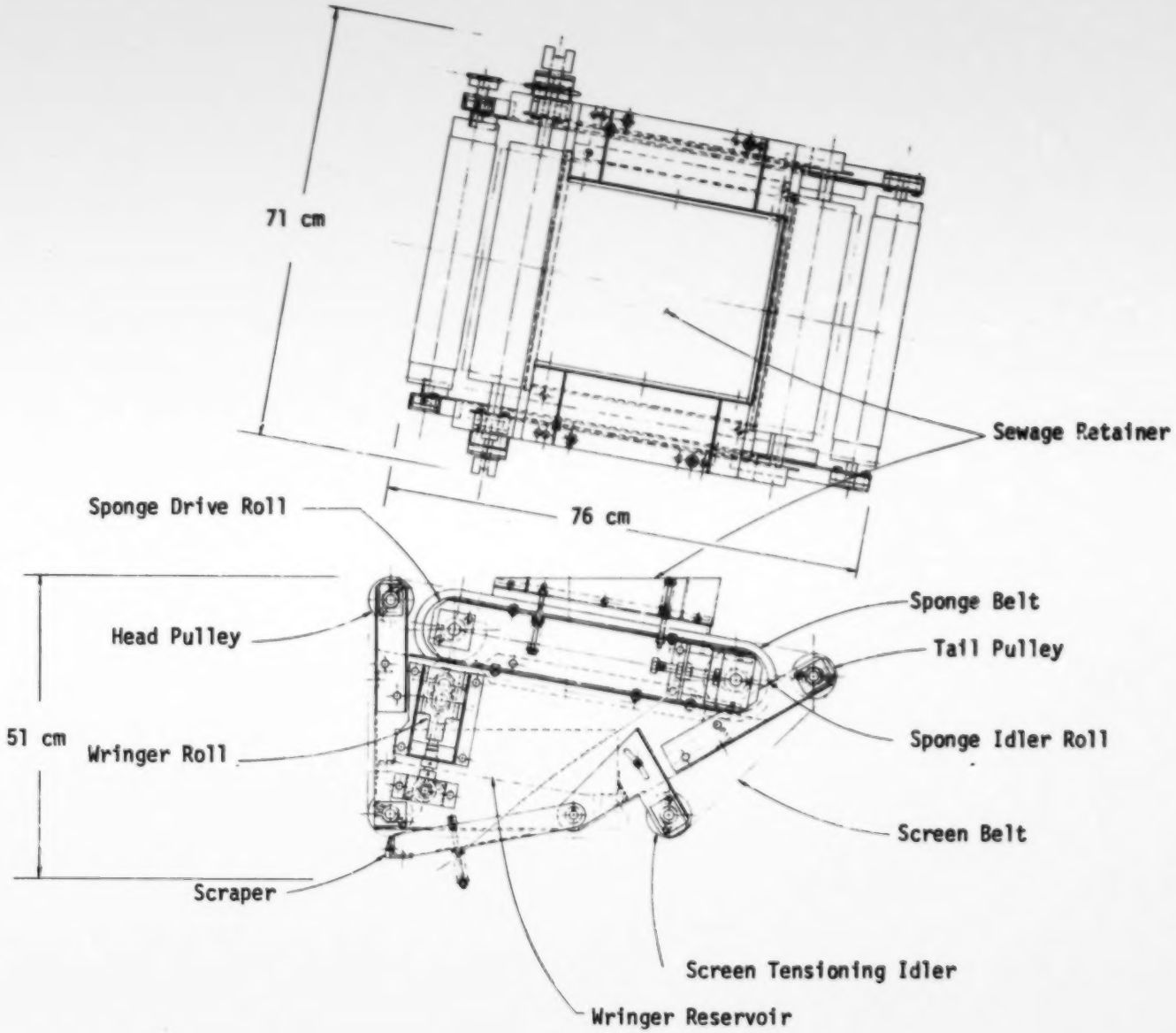


Figure 12 MOVING SCREEN FILTER (MSF) ASSEMBLY DRAWING

The screen belt and underlying sponge belt remain in contact for approximately 23 cm before separating; this adequately allows the liquid to be drawn through the sponge during a 10-second period. The screen belt with retained solids continues around the head pulley, down past the scraper and scraper support idler, horizontally back past the screen belt tensioning idler, up past the screen spray to the tail pulley, and back to the feed position.

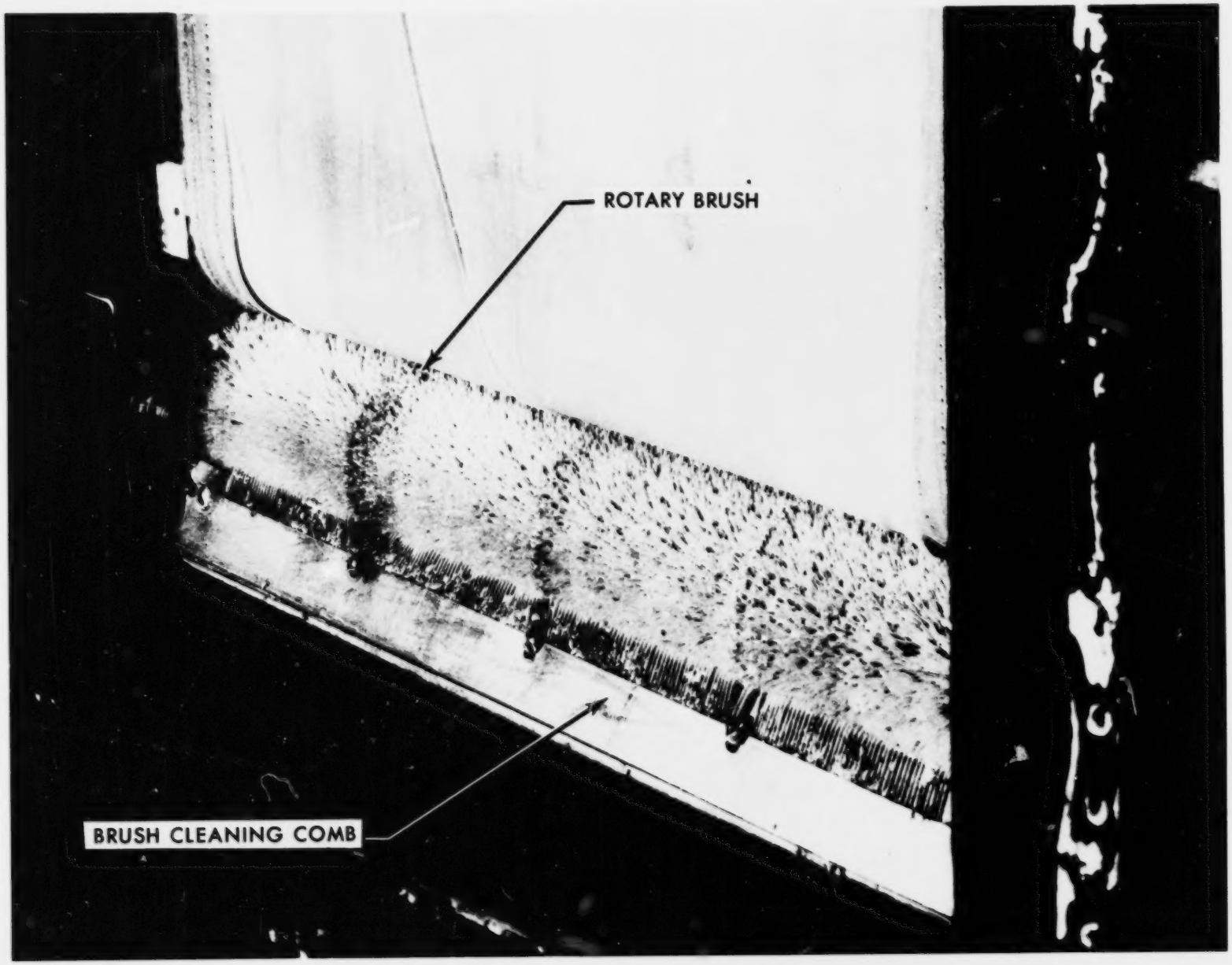
The sponge belt, supported between the sponge drive roll and idler roll, is located so that the upper portion of the sponge and the screen are in contact at the feed position. The water absorbed at the feed position is carried in the sponge belt, around the drive roll, to the wringer roll where the sponge is compressed between the wringer and drive rolls. The entrained water is squeezed from the sponge and drains to a reservoir beneath the wringer for subsequent supply to the effluent feed pump.

During the testing of the full size unit it was discovered that fibrous material present in the sewage could not be effectively removed with the rubber scraper indicated in Figure 12. The bulk of the solid fibrous matter retained by the screen was primarily tissue paper, which proved to be extremely difficult to remove with only a rubber scraper. Several scraper arrangements were evaluated using various grades and widths of rubber and plastic blades, but none proved satisfactory in removing the fibrous materials.

The paper which remained on the screen after the scraper was removed by the screen belt sprays and returned with the spray water to the MSF for reprocessing. Although this resulted in a workable process, it did place an added burden on the MSF since the recycling of solids through the return pump resulted in mechanical break-up of solids and reduced filter efficiency. To overcome this solids removal problem, the rubber scraper was replaced by an 8-cm diameter brush rotating at 200 to 300 rpm; the brush proved effective in removing tissue paper and other wastes from the screen. The brush assembly is shown in Figure 13.

During operation mechanical problems with the MSF were minimal. However, if the system was not operated for several days the cellulose sponge belt would dry out and damage to the sponge belt could occur if the device were started in this dry condition. To prevent damage to the sponge belt, a slip clutch was included in the MSF drive train. To prevent drying of the sponge the device should be run briefly every ten hours to maintain the belt moist and flexible.

Urethane sponge does not become brittle when dry and in this respect would offer substantial improvement over the cellulose sponge material. A sponge belt was fabricated from urethane but proved to be unacceptable due to excessive (20% to 30%) expansion of the sponge when wet. It is probable that a urethane sponge belt can be designed in which the detrimental effects of sponge expansion can be minimized; however, since the cellulose sponge belt was functionally acceptable, further evaluation of the urethane sponge belt was not pursued.


ROTARY BRUSH
BRUSH CLEANING COMB

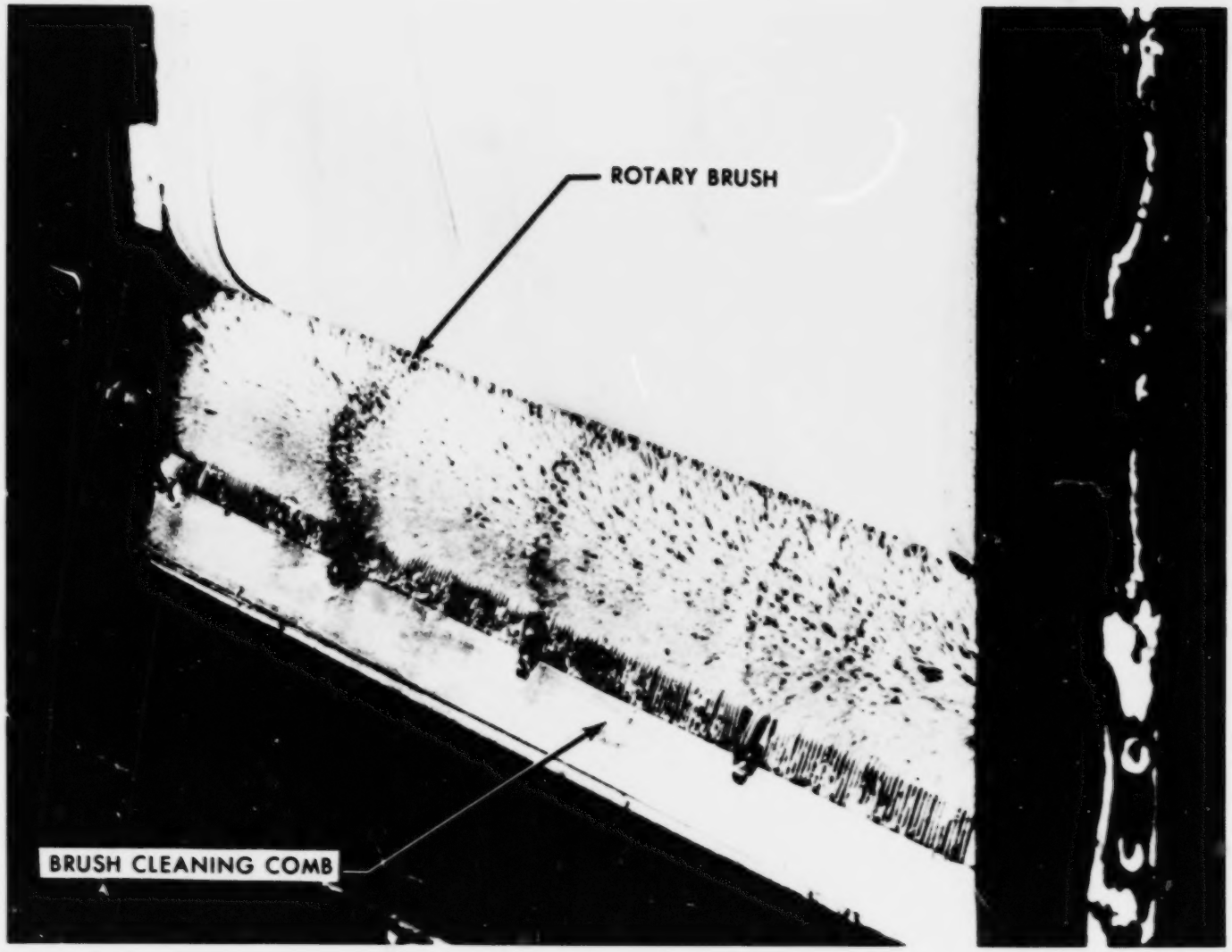


Figure 13 ROTATING BRUSH

The MSF device is housed within the feed tank support structure as shown in Figure 14. During normal operation the filter device is completely enclosed to contain any odors associated with the raw sewage being processed by the MSF. Any required maintenance can be performed on the filter by removing the side panels shown in Figure 15 or by sliding the mechanism from the support frame onto a fixture as indicated in Figure 16.

Pressure Filter

A pressure filter of the same type used on the laboratory model was installed in the full scale unit as planned. The major components in the filter are the filter bed, cleaning system, circulating pump, and flow valves. To automate the backwash procedure, all flow-directing valves were solenoid operated. In the initial tests the 2-cm valves selected had sliding self-cleaning Teflon seats with 0.5-cm orifices. In a period of two to three hours of operation these valves became inoperative when the filter media became lodged in the valve seat recess. These valves were replaced with motorized 2-cm ball valves with 1.6-cm orifices which operated satisfactorily throughout the remainder of the test program.

The pressure filter unit was consistently able to remove a high percentage of the 1- to 2-micron particles from the MSF effluent. The only serious problem encountered with the unit was the coalescence of the filter media caused by what appeared to be slime mold. This slime mold developed after several weeks of operation with sanitary sewage and could not be removed by mechanically backwashing the media.

During normal operation in the initial tests, the pressure drop across the filter remained below 0.07 atm for approximately one hour, rose gradually to 0.3 atm,in the next half hour, and then rose to 1.4 atm at a total elapsed time of two hours. Backwashing the filter with approximately twenty liters of filtered water was sufficient to clean the media so that the same filter cycle could be reproduced. After two weeks of operation, a brown scum began to appear in the packed media and at the surface of the bed. This scum or slime caused the media to coagulate and resulted in shorter periods between backwashings. During the backwash cycle the coagulated media would tend to clog the recirculating lines and the cleaning septum so that cleaning the media became a major problem. As much as 60 liters of water was required to remove the particulates from the media while the subsequent filtering period with the cleaned media would get progressively shorter. The filtering period eventually ranged between 20 and 60 minutes, depending on the concentration of the processed sewage.

During the laboratory tests with the same type of filter, filtration periods of four to six hours were normal before backwashing was required. This was attributed to the processing of formula 2 sewage which contained a small percentage of feces. In the full scale unit, the processed sewage was predominantly feces containing small micron-sized particles which passed through the MSF and eventually were trapped in the pressure filter. Bacterial growth in these particles resulted in the formation

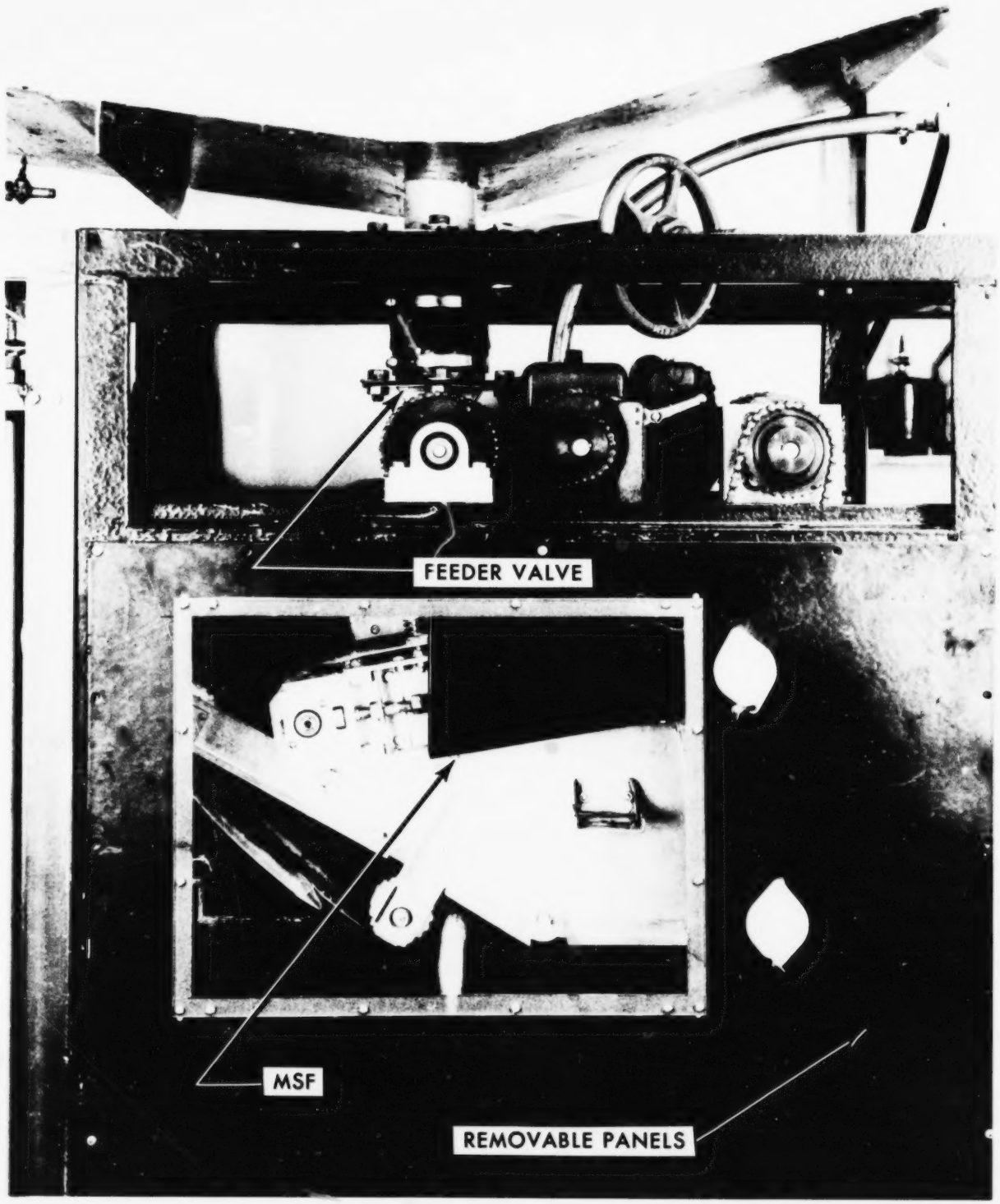

FEEDER VALVE
MSF
REMOVABLE PANELS

Figure 14 MSF DRIVE ASSEMBLY AND HOUSING

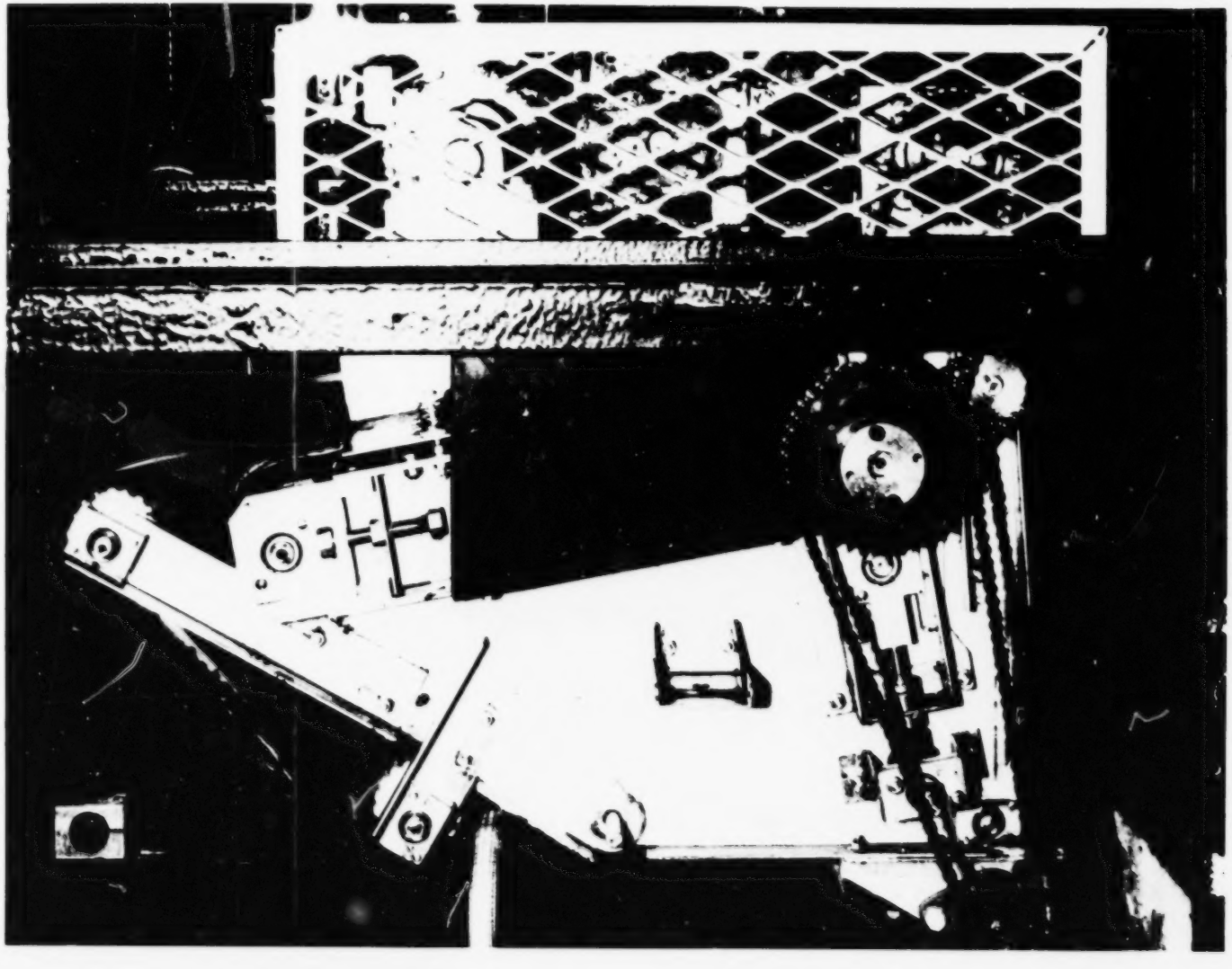
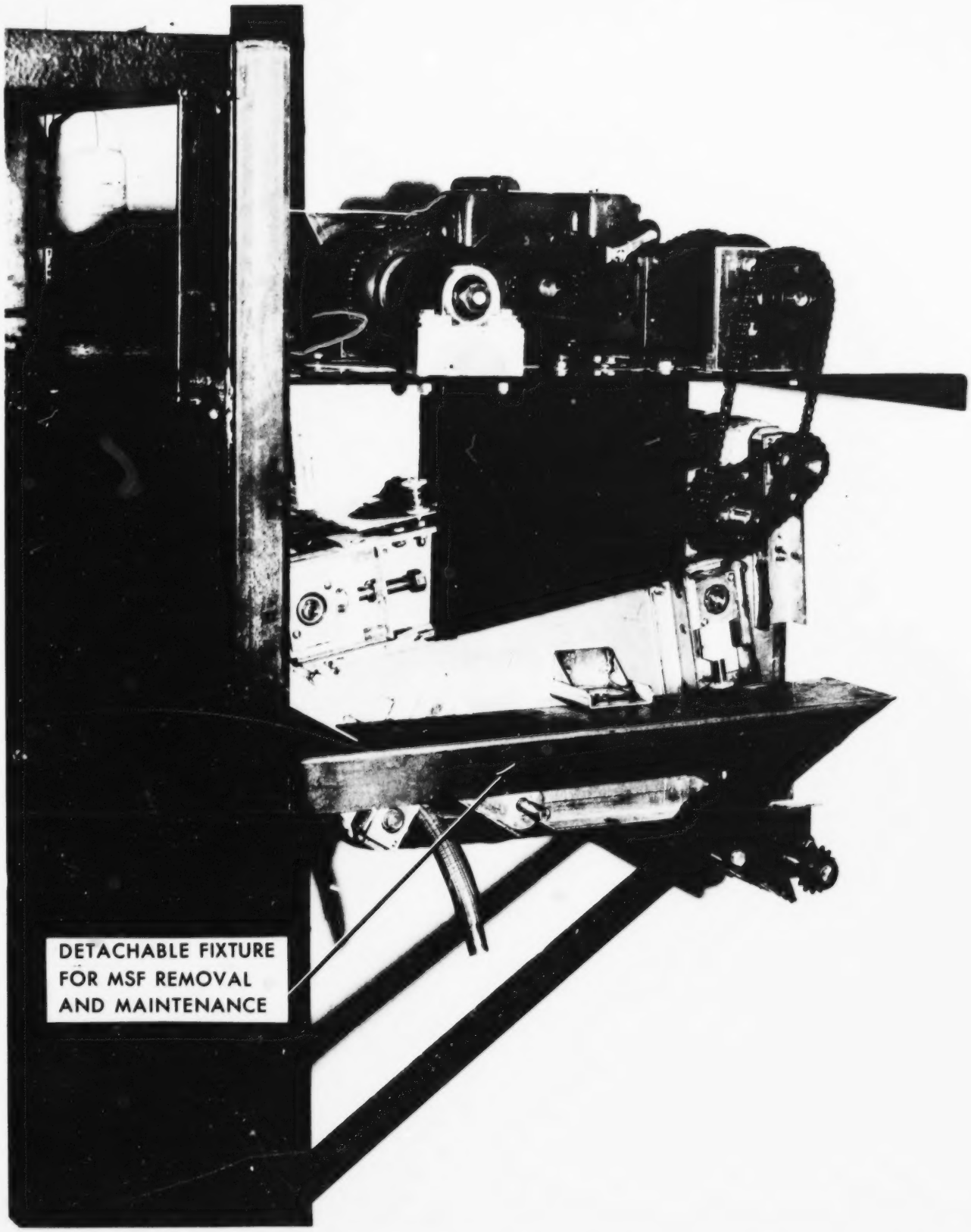


Figure 15 HOUSING AND DRIVE PANEL REMOVED



DETACHABLE FIXTURE
FOR MSF REMOVAL
AND MAINTENANCE

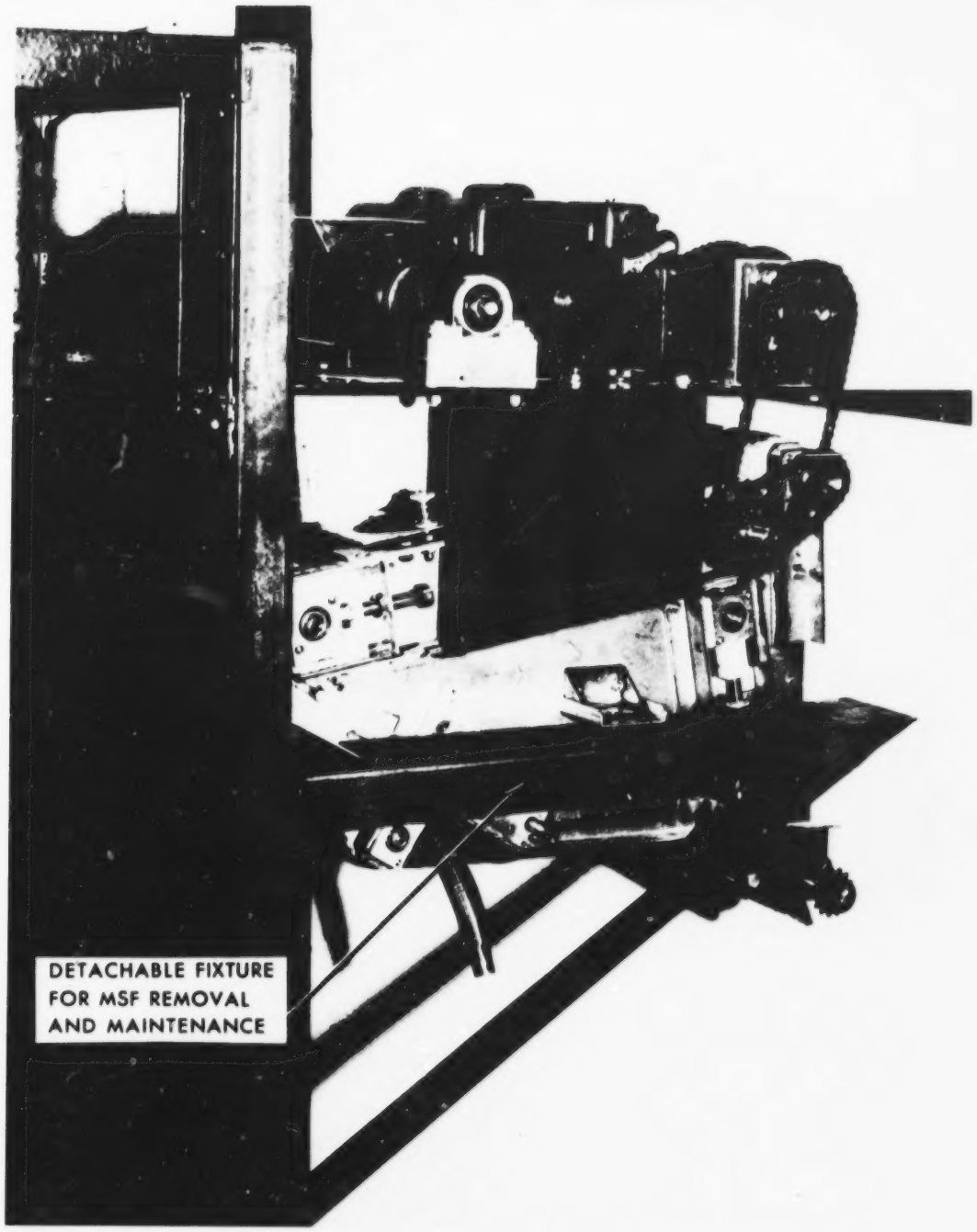


Figure 16 MSF SUPPORT FRAME SLIDE ARMS

of slime which caused the media to coalesce, thus preventing removal of the particles through the cleaning septum.

In considering these conditions, it was decided to reduce the amount of micron sized particles reaching the pressure filter by increasing the filter efficiency of the MSF. Ferric chloride was added to the wastes supplied to the MSF to coagulate the particles of 30-micron size and smaller which were passing through the MSF. The effect of the ferric chloride in the waste stream however also resulted in the coagulation of the media in the pressure filter and plugging of the bed.

If the filter unit is to be incorporated into the system, it would be necessary to operate the unit with influent which has already been disinfected to prevent the formation of slime in the filter. This could be accomplished by placing the pressure filter device after the chlorinator.

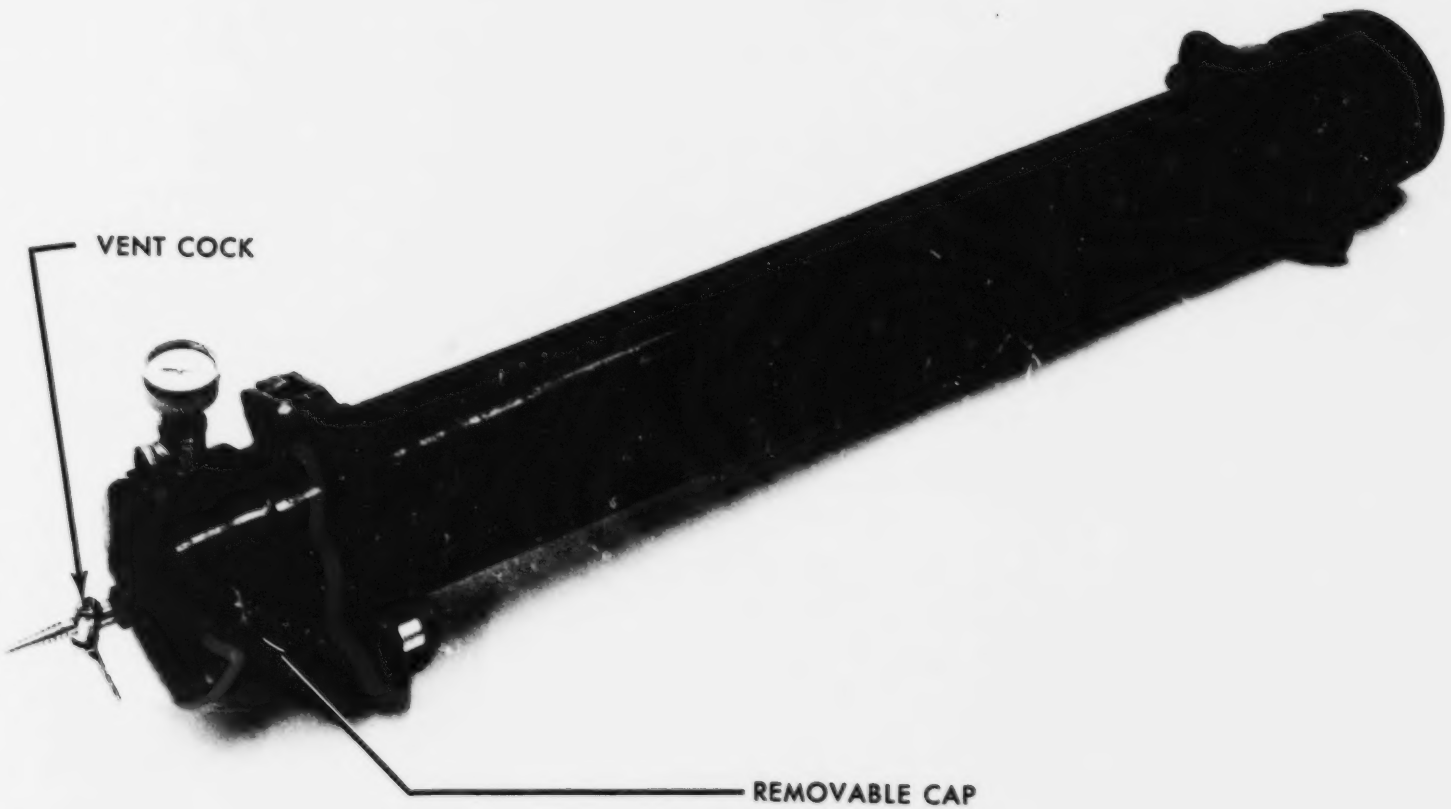
Carbon Adsorption Beds

In the full size unit six carbon adsorption columns were arranged in an upflow configuration to prevent plugging of the bed. Both one, two, and two pairs of three beds in series were used in various phases of testing.

The final configuration of one of the carbon column beds is shown in Figure 17. The bed is approximately 150 cm high and was fabricated from 15-cm diameter, schedule 80 (14.4 cm ID) PVC pipe. Each end of the column has a removable cap which contains a stainless steel impingement screen retaining support. The caps are secured by pipe couplings to permit removal for servicing, or to replace the carbon when required. Each cap has a gas cock to permit the column to be vented during the initial filling with water.

The effective bed height of each column was 138 cm. The six beds were connected in two pairs of three beds in series to give a total residence time of approximately 17 minutes, when operated at the design rate of 4 l/min. Initially the beds were filled with a commercially available activated carbon, "Calgon Filtrasorb 300", which after being washed and drained of water has a bulk density of 417 kg/m^3 and mean particle diameter of approximately 1.6 mm. During the initial tests, it appeared that the suspended solids passing through the pressure filter were being trapped in the carbon beds, with the possibility that the bed might become plugged and that bacterial growth might occur in the bed, causing further plugging. The activated carbon in the beds was replaced with "Calgon Filtrasorb 400", wich has a mean particle diameter of approximately 0.6 mm. This finer media was used to provide better fluidization of the bed in upflow so that the suspended solids would pass through the bed, thus preventing the beds from becoming plugged. The remainder of the tests were conducted with the finer carbon media.

The carbon columns are connected in series with quick disconnect hose fitting to permit the units to be easily removed and replaced. Since each column weighs only 25 kg, individual units can be serviced by one man.


VENT COCK
REMOVABLE CAP

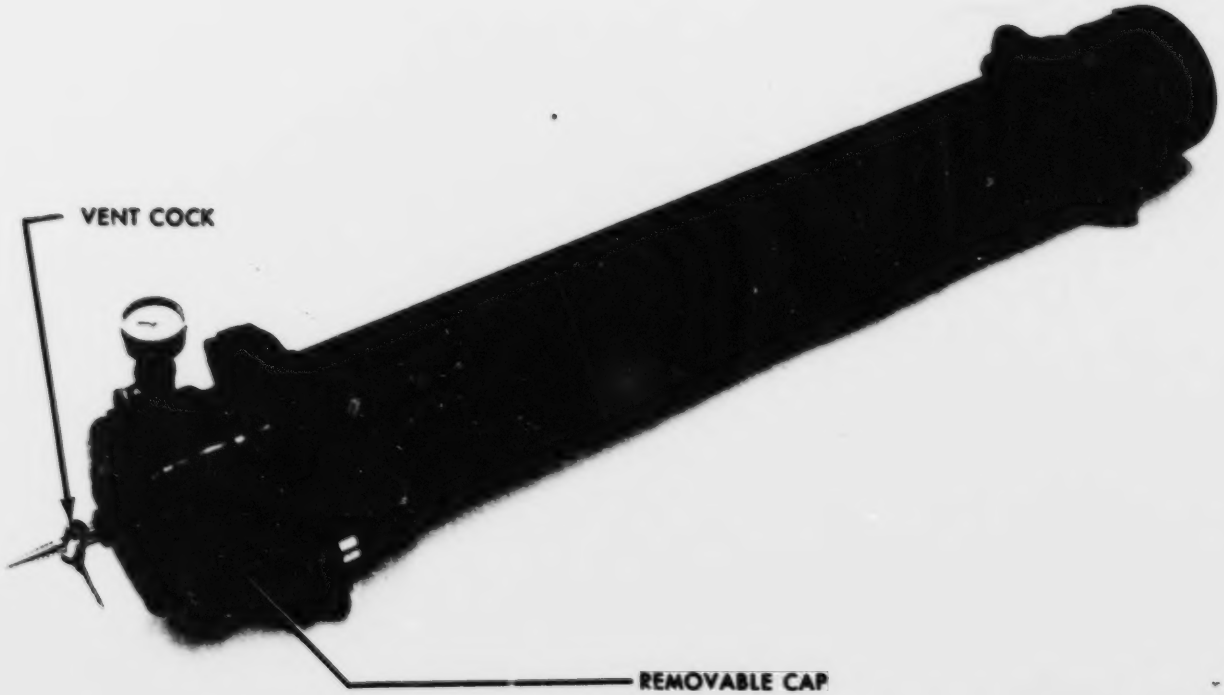


Figure 17 CARBON BED CONFIGURATION

Chlorination Unit

The hypochlorite feed pump and contact tank, used in the chlorinator for the laboratory prototype system, performed satisfactorily in the initial full scale system tests but a unit was also used which appeared more appropriate for unattended shipboard service. The unit was designed originally to be used in chlorinating swimming pools. The unit uses calcium hypochlorite tablets which contain 70% available chlorine. At the design flow rate of 2650 l/day for the system, it was expected that a 2.3 kg supply of tablets would last approximately one week. A sketch of this chlorination unit is indicated in Figure 18. The unit operates as follows: effluent from the carbon columns enters the syphon tank at a constant rate and the tank fills until flow is initiated in the syphon tube. The syphon tube quickly empties the tank, breaking the syphon and interrupting the flow to the contact tank. The flow from the contact tank is restricted by a calibrated discharge orifice which causes the level in the contact chamber to rise to a constant level during each cycle. The hypochlorite tablets are supported in a plastic basket which extends into the contact chamber. Since the level in the contact chamber always attains the same height, the amount of tablets in contact with the influent can be controlled by adjusting the neight of the tablet basket. The water level in the contact chamber rises and falls below the basket during each cycle, producing a washing effect on the tablets and eliminating caking of the dissolving talets. No mechanical problems were experienced with the chlorination device, since the device has no moving parts.

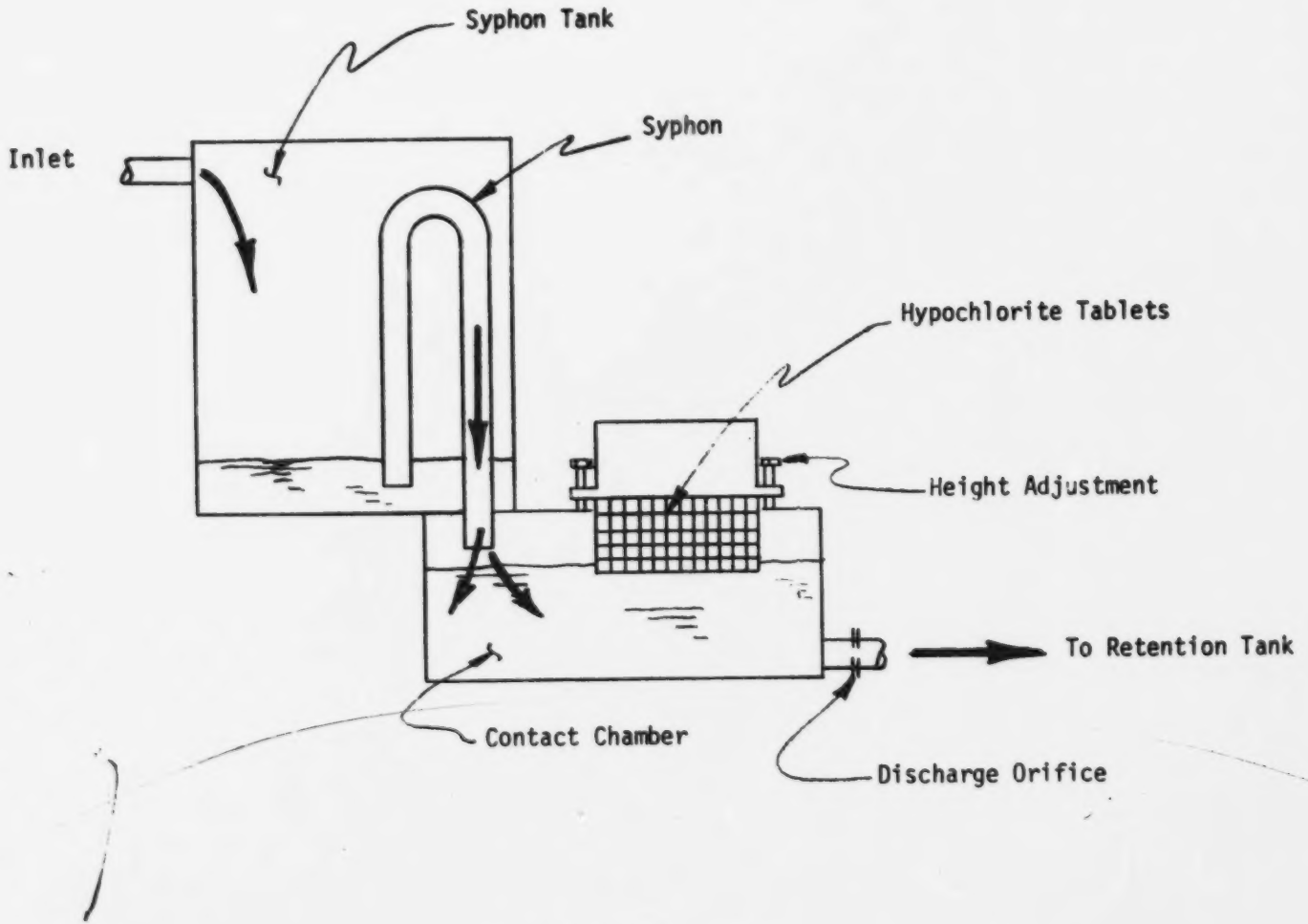


Figure 18 CHLORINATOR

SECTION V

SYSTEM PERFORMANCE TESTS

The sources of the waste material expected aboard ship fall into four categories--toilet facilities, galleys, washbasins, and showers. Preliminary estimates indicated that the composite waste stream from all shipboard conveniences would typically contain on the average 750 mg/l SS and BOD. Although the contributions from each waste source are subject to wide variations during a normal day, it was assumed that over extended operating periods of weeks or months the bulk of solids would originate in the toilet facilities and galley and that a representative wastes mixture could be prepared by adding toilet wastes and food items to appropriate quantities of water.

Laboratory System Tests

In the laboratory test program representative waste mixtures were prepared in the inlet feed tank to achieve approximately a 750 mg/l concentration for SS and BOD levels. Food and vegetable matter, feces, urine, and other waste items such as toilet tissue were added to tap water to achieve the desired solids concentration. The formulations of the simulated sewage used in the majority of system tests were as follows:

Waste Items	Formula 1 Dry Weight (gm)	Formula 2 Dry Weight (gm)
Canned Potatoes (cooked)	49	21
Canned Carrots (cooked)	49	21
Bologna	14	14
Toilet Paper	7	7
Peanut Butter	14	14
Soap	7	7
Feces	0	57
TOTALS	140	141

The amount of dry solids indicated was added to approximately 190 liters to give about 750 mg/l of solids. In Formula 2, 1600 ml of urine was also added to the 190-liter mixture.

In the preliminary tests using the laboratory prototype system all solids in both formulations were passed through a kitchen sink disposal unit before being added to the tap water. The solids were kept in suspension by placing a stirring device in the feed tank. Determinations of SS and BOD in all wastes streams were made by Standard Methods.

Moving Screen Filter

Initially, the laboratory tests were directed towards developing the mechanical aspects of the moving screen filter, but spot checks were made on the filtering efficiency during this period. Typical results obtained with the single belt filter device are indicated in Table 1 below. Although the calculated SS level was 750 mg/l, the actual measured level in the raw feed was as indicated.

TABLE 1

SINGLE BELT MOVING FILTER

Wastes Formula	Test Volume (liters)	Suspended Solids, mg/l		
		Raw Feed	MSF Effluent	% Reduction
1	200	342	118	65
1	200	481	168	65
1	200	435	214	51

During this test series it was noted that the filtration efficiency was gradually reduced as oil and grease from the sewage blinded the filter screen. By spraying the screen with water after filtration, the permeability of the screen could be restored. Some of the spray water was absorbed by the sponge and consequently reduced the filtration rate.

As noted previously, a dual belt system was next tested; the dual belt configuration permitted the screen to be spray-cleaned without adding unnecessary water to the sponge.

During testing with the dual belt configuration, the effluent from the screen filter was passed downflow through one carbon column. The results of these tests are tabulated in Table 2.

TABLE 2

PROTOTYPE DUAL BELT MSF WITH ONE 15-CM DIAMETER,
75-CM DEEP CARBON COLUMN

Waste Formula	Test Volume (liters)	Suspended Solids, mg/l		
		Raw Influent	MSF Effluent	Carbon Effluent
2	190	624	260	---
1	190	750 (est.)	88	12
1	190	750 (est.)	170	16
1	190	247	203	23

As can be seen from the test results, the quality of the effluent from the MSF showed significant differences in this short test series. In the first test the simulated sewage consisted of Formula 2 wastes which included feces; in the remaining tests Formula 1 wastes were used.

In these tests the reduction in SS across the carbon co umn indicated that the carbon column was acting as a filter, and although the effluent quality was excellent, the suspended solids which were retained in the carbon bed caused plugging of the column near the end of the third test run.

In two separate tests samples of as-collected feces alone, in water, were fed manually by gravity to the filter screen. Each sample weighed approximately 100 grams, and was added to 4 liters of water. The feces and water were not passed through a macerator or pumped, but were poured onto the filter screen from a height of 20 cm. The feces remained intact, without disintegration, and no visible solids could be seen in the water that passed through the screen. No measurement of the SS level was make, but the removal efficiency was estimated at over 95% by weight.

Bed Filters

From early tests it was concluded that additional filtration of the MSF effluent would be necessary to achieve the desired reduction in SS when the waste stream contained a large percentage of ultrafine solid materials. Although it was anticipated that the solids particle-size distribution in an actual shipboard waste stream with a predominance of large size particles (over 50 microns in diameter) would be much more favorable than the simulated wastes, an evaluation was made of secondary filtration devices which would remove smaller particles and which could be easily adapted to shipboard service. Gravity-type dual-media bed filters were fabricated and tested, using various types of anthracite, sand, and gravel media commonly used in water and waste treatment, and a pressure-type filter using a synthetic media, were tested in the MSF system using media indicated in Table 3.

TABLE 3

SIZE OF MEDIA TESTED IN BED FILTERS

	Media	Size Distribution
(1)	Gravity Bed	
	#20 Gravel	1.25 mm - 1.75 mm
	#30 Gravel	0.08 mm - 1.20 mm
	# 3 Anthracite	1.50 mm - 2.00 mm
(2)	Pressure Bed	
	Polystyrene resin	0.30 mm - 0.42 mm

Fifteen-cm diameter gravity bed filter columns were constructed and operated with a flow rate of 3 l/min, resulting in a loading of 164 l/m^2-min. A commercially available 10-cm diameter pressure bed filter was also operated with a flow rate of 2.3 l/min, resulting in a loading of 278 l/m^2-min.

The reduction in suspended solids achieved with the MSF and filter bed columns employed is shown in Table 4. In these tests Formula 2 simulated sewage, including feces, containing approximately 750 mg/l SS wss used as the feed to the MSF unit.

TABLE 4

REDUCTION OF SUSPENDED SOLIDS
MSF AND FILTER BED CONFIGURATIONS

		Suspended Solids (mg/l)	
Filter Bed Type		MSF Effluent	Filter Bed Effluent
(1)	Gravity -- 15 cm Diameter # 3 Anthracite #20 Gravel - 60 cm deep	128	94
(2)	Gravity -- 15 cm Diameter # 3 Anthracite - 15 cm deep #30 Gravel - 60 cm deep	248 194	210 138
(3)	Pressure -- 10 cm Diameter Type "O" Resin - 30 cm deep	160	75

As the results show, the performance of a pressure-type filter using a polymer resin filter media proved to be superior to conventional gravity-type gravel bed filters in reducing SS. In addition, the method described in Section IV that was used to backwash the media in the pressure filter gave promise of providing extremely long filter life.

Early performance tests using this secondary pressure filter unit indicated that the SS in the waste stream could be readily reduced to or below the 100 mg/l level. During filter runs of approximately 400 liters at a rate of 3 liters per minute, the pressure drop across the filter would increase gradually but would not exceed approximately 0.27 atm at the end of the filter run. After backwashing, the pressure drop across the filter would be returned to a level less than 0.07 atm. The manufacturer of the pressure filter indicated that the efficiency of the filter could be expected to improve as this pressure drop increased with usage.

Based on these early results, it was anticipated that filter performance could be easily maintained at design capacity with a maximum pressure drop of 1.4 atm with only one or two backwash cycles per day. Consequently, the laboratory system was revised to include a full scale pressure filter with a 15-cm diameter, 60-cm deep bed. The filter was designed to use Type "O" polymer resin. The results obtained with this and a 10-cm diameter pressure filter are shown in Table 5.

TABLE 5

REDUCTION OF SUSPENDED SOLIDS
MSF AND PRESSURE BED FILTERS

	Suspended Solids, mg/l				
Test Volume (liters)	Raw Feed	MSF Effluent	Press.Filt. Effluent	Carbon Bed Effluent	Overall % Removal Effic.
380	508	207	90	72	86
370	546	196	59	--	89
360	415	174	106	44	89

The large reduction in suspended solids which was noted across the pressure filter indicated that the probability of achieving overall system removal efficiencies of 90% SS would be improved considerably by including a pressure filter unit of this type in the system. In this test series overall removal efficiencies of between 75% and 90% were being attained with macerated sewage containing food wastes, urine, and feces.

Carbon Column and Effluent Chlorinator

The laboratory system was operated in most tests with a carbon bed for treating effluent from the MSF and bed filters. However, no BOD removal efficiency measurements were taken until the SS level entering the carbon bed was effectively lowered to the 100 mg/l level since the sorption capability and continued operating life of the carbon bed depended on prevention of plugging of the bed. With the MSF and pressure filter operating together the inlet SS level to the carbon beds was held below the 100 mg/l level, and, as noted in one test, the amount of SS removed by the carbon beds was relatively low, indicating a reduced probability of rapid plugging with solids.

Prior to operation with the pressure bed filter, a single 15-cm diameter by 75-cm high carbon bed was used in downflow after the MSF; the bed contained activated carbon, Calgon Filtrasorb 400, with a nominal particle diameter of 0.7 mm. This bed was subject to plugging after only several hours of operation. After the pressure filter was added, the carbon bed operated properly but still showed some signs of plugging after 10 to 15 hours of operation.

To minimize plugging and to achieve proper BOD removal efficiency, another carbon bed was added in series to the system. Filtered effluent passed downflow through the first carbon bed which was changed to Calgon Filtrasorb 300 activated carbon with a nominal particle diameter of 0.9 mm. The second carbon bed was operated in upflow, with a nominal particle size of 0.7 mm; this carbon bed was fluidized with 5%-8% expansion of bed height, at a flow of 3 liters per minute, or 164 l/m^2-min.

The two carbon beds in series operated for over sixteen hours without apparent plugging and reduced the BOD content to the levels shown in Table 6 when treating Formula 2 wastes. These tests indicated that the overall system was capable of reducing the BOD level with an approximate efficiency of 90%.

TABLE 6

PERFORMANCE OF TWO CARBON BEDS IN SERIES
MSF AND PRESSURE BED FILTERS

Test Volume (liters)	Raw Feed	MSF Effluent	Press.Filt. Effluent	Carbon Beds Effluent	Overall % Removal Effic.
360	720	400	312	56	92
380	955	548	355	92	90
370	750	410	180	82	89

During tests where the MSF, pressure filter, and carbon beds were operating at SS and BOD removal efficiencies approximating 90%, the effluent from the last carbon bed was passed through a baffled 50-liter chlorination tank. At a flow rate of 3 l/min, the average stay time in the tank was approximately 17 minutes. The purpose of this final treatment step was to determine the probable amount of chlorine needed to control coliform for the SS and BOD levels remaining in the effluent. With the SS level in the 50 to 100 mg/l range, and BOD in the 60 to 80 mg/l range, actual tests indicated that an input chlorine dosage level of 50 mg/l was needed to achieve a residual chlorine level of 0.5 to 2.0 mg/l. Operation at this dosage level was considered adequate to ensure reduction of coliform below the required 240 MPN/100 ml level.

Full Scale System Tests

Prior tests with the laboratory prototype system had indicated that the fecal material in the sanitary sewage would be the most difficult to remove; consequently, a decision was made to process primarily only sanitary waste from toilets during tests of the full scale system. The reasons for this course of action were:

1. Based on laboratory system tests with Formula 1 wastes, the galley waste material would be generally easily removed by the MSF.

2. The character of actual galley waste material will be subject to wide variation, and it would be difficult to predict shipboard performance from laboratory results obtained with simulated galley wastes.

3. By using only sanitary wastes, a burden would be placed on all system components. If system performance and reliability could be established using sanitary wastes exclusively, it would be expected that in shipboard service the actual system performance would be superior to that experienced in the laboratory test program.

Waste Treatment System with Pressure Bed Filter

Tests were performed on the moving screen filter, pressure bed filter, and carbon columns with sewage transferred from a sewer sump to the filter system by a centrifugal sump pump. The objective was to deliver sanitary wastes to the system in substantially the same condition that would occur aboard ship; however, the centrifugal pump, which would nominally pass 4-cm solids, caused substantial disintegration of the soft fecal solids. This seriously reduced the efficiency of the MSF and placed a heavy burden on the pressure filter unit.

As a result, the sewage processed during this test series contained a much greater share of disintegrated fecal material than would be expected during actual service aboard a vessel. The ultrafine fecal particulates are not removed by the MSF since the average particle size is well below the 30-micron openings in the MSF filter screen. Based upon visual microscopic examination, it was estimated that over 90% of the particles that did pass the MSF were in the 1-2 micron range, with the remainder in the 2-25 micron range.

The results of tests with the finely macerated wastes are shown in Table 7. These tests showed that the MSF and pressure filter operated satisfactorily, for solids removal, and achieved an overall SS removal efficiency averaging approximately 60%, even with feed containing well-macerated fecal wastes having significant amounts of particles below 30 microns in diameter. This removal efficiency was similar to original results achieved with the laboratory system. However, the tests also showed this system including two carbon columns achieved an overall BOD removal efficiency averaging approximately only 60%. Also, the BOD level from the filters to the carbon column was well over the 100 mg/l level recommended for adequate BOD removal in continuous operation.

Since particulate loading on the pressure filter was much higher than would be encountered in actual service, it was anticipated that the filter would also require more frequent backwashing to maintain a reasonably low final pressure drop, in the 1.4-2.0 atm range. At the beginning of this test series the pressure drop across the filter was

TABLE 7

SS AND BOD REMOVAL TESTS: MSF, PRESSURE FILTER, AND TWO CARBON BEDS IN SERIES
(RAW SEWAGE PUMPED CENTRIFUGALLY FROM SUMP BASIN)

Test Volume (liters)	Suspended Solids (mg/l)				BOD (mg/l)			
	Raw (Feed)	MSF (Effluent)	Press.Filt. (Effluent)	Carbon Bed (Effluent)	Raw (Feed)	MSF (Effluent)	Press.Filt. (Effluent)	Carbon Bed (Effluent)
620	390	233	109	70	275	282	148	89
465	178	125	60	24	---	---	---	---
420	222	145	37	31	195	157	117	95
357	358	150	38	26	293	278	200	123
480	718	337	123	67	315	176	156	67
620	342	245	81	53	255	150	123	99
290	353	221	83	72	210	180	135	109
338	1860	752	754	390	---	---	145	144

typically 0.07 atm at the start and approximately 0.9 atm at the completion of a test run. At the completion of each 2- to 4-hour test the filter was backwashed, but as the test continued, both the starting and final pressure drops across the filter began to increase. An arbitrary final pressure maximum of 2 atm was selected to establish when the filter should be backwashed. As testing continued, the necessity of backwashing became increasingly frequent and the character of the filter media in the pressure filter began to change.

The filter media has a natural chalk-white color, and in water it forms a free-flowing suspension. In early tests the filter bed would pick up some color from particulates during a filter run, but backwashing would restore the bed to its original white color. As testing progressed, the media assumed a grayish color which was not removed by backwashing, and the filter media began to agglomerate. The formation of what appeared to be a visible slime mold within the filter bed caused coalescence of the media particles into clusters which could not be disintegrated by mechanical agitation during the backwash cycle. The clusters of media rose to the top of the pressure filter during backwash and totally clogged the exit piping; disassembly and replacement of the filter media was required for resumption of operation.

It appeared that the pressure bed could be operated on a continuous basis if build-up of slime could be stopped. Since the presence of slime was probably due to growth of microorganisms, it might have been feasible to eliminate this growth by (1) addition of growth inhibitors to the bed influent, or (2) periodic aeration of the bed, possibly during backwashing.

Although the pressure bed filter in conjunction with the MSF demonstrated a commendable capability to remove suspended solids, the bed and attendant cycling control did increase the complexity of the total waste treatment system to an extent which might be too complicated for smaller marine vessels. To minimize potential system complexity, and to permit testing of other system configurations, further testing of the presuure bed filter was discontinued.

During tests with the pressure filter, the effluent from the carbon beds was passed through the chlorination contact tank at 3.5 l/min. A water solution of 5.25% chlorine (laundry bleach) was added to the tank at a rate of 3 ml/min to provide the 50 mg/l of chlorine found necessary for coliform reduction. The solution was normally added continuously during the operation of the treatment system.

Waste Treatment System with Vacuum Transport of Wastes

After removal of the pressure filter, the MSF system was tested in the basic configuration consisting of the MSF filter assembly, carbon adsorption columns, and the chlorination unit. Although this system had been unable to achieve the desired 90% reduction in SS and BOD when processing macerated sanitary waste material containing large percentages of fine particles, it was expected that removal performance would improve substantially if disintegration of the fecal material could be reduced.

The waste collection apparatus which had been used during the evaluation of the MSF and pressure bed filter consisted of a centrifugal transfer pump, piping, and a catch basin which collected all waste materials from a lavatory with one commode, one urinal, and one washbasin. Waste material flowed by gravity in from the lavatory in 10-cm soil lines to the catch basin sump located 10 meters from the lavatory. Material which collected in the catch basin was transferred through 4-cm hose to the wastes/feed tank by a submersible centrifugal sump pump located in the catch basin. Although this transfer pump was capable of passing 4-cm diameter solids, it was observed that the fecal material was being substantially reduced in size during the transfer between the catch basin and the feed tank. This size reduction was attributed to the violent agitation occurring in the centrifugal transfer pump and to the high velocity turbulent flow through the hose.

To reduce mechanical agitation of the wastes, the centrifugal pump was replaced by a vacuum transfer system.

A series of performance tests were run with the revised transfer system. In these tests composite samples were obtained of the MSF and carbon column effluents. Since difficulty had been experienced during earlier full scale tests in obtaining representative samples of raw waste, all solids removed by the MSF were collected and dried. The total amount of solids in the original raw sewage was then calculated by determining the weight of dry removed solids per volume of sewage processed by the MSF (mg/l) and adding this value to the SS measured in the MSF effluent.

The results of this test series are indicated in Table 8. As in previous tests, only sanitary wastes were processed during the test series, and only two carbon columns were in service.

These results indicated the MSF was still not capable of removing SS with a sufficiently high efficiency. The amount of particulates below 30 microns in the wastes appeared less with vacuum transport than when pumped with the centrifugal pump. However, the amount was still sufficient to prevent adequate removal of solids by the MSF.

The resulting SS level in the influent to the carbon beds averaged 215 mg/l which was well above the desired level of 100 mg/l, considered as a maximum for satisfactory BOD removal by the carbon bed. During the first five of the tests listed, one carbon bed was in upflow operation using 0.80-0.90-mm granules, and in the next five tests using 0.55-0.65-mm granules. In the last eight tests two carbon columns were in operation in series, the first in downflow with the coarser granules, and the second in upflow with finer granules. Comparison of performance between the single and dual column configuration is not conclusive, primarily because influent SS and BOD levels were inordinately greater than recommended for carbon adsorption of solubles.

During tests with the vacuum transport system the effluent from the carbon columns was normally treated in the 60-liter contact tank with a 5.25% solution of chlorine in water at a constant rate of 3 ml/min to maintain the input chlorine level at 50 mg/l. Due to changes in effluent flow rate that typically occurred in system testing, the input chlorine level changed sporadically.

TABLE 8

SS AND BOD REMOVAL TESTS: MSF TREATMENT SYSTEM WITH VACUUM TRANSFER OF WASTES

Test Volume (liters)	Suspended Solids (mg/l)			BOD (mg/l)		
	Raw (Feed)	MSF (Effluent)	Carbon Bed (Effluent)	Raw (Feed)	MSF (Effluent)	Carbon Bed (Effluent)
435	490	225	---	165	97	---
102	2350	310	160	1350	682	278
882	435	108	83	323	132	92
416	540	191	137	645	270	154
299	900	250	---	885	345	---
151	700	253	---	510	352	---
333	665	166	60	815	166	90
174	334	172	52	570	172	110
379	453	224	234	690	334	265
723	474	232	147	600	232	121
609	360	118	118	885	118	120
379	711	238	211	668	238	225
621	534	154	75	1380	319	172
337	1154	256	300	720	337	330
318	401	135	73	510	465	440
492	496	210	103	510	386	234
568	651	307	157	472	435	254
379	823	333	---	1030	300	---
Average:	693	215	136	707	292	206

To overcome these variations in chlorine levels, the calcium hypochlorite and water-syphon system was substituted in the last three tests listed. In these tests effluent from the carbon beds passed through a water-syphon tablet chamber at an averaged flow rate of 3.5 l/min; the amount of chlorine added to the stream was controlled by adjusting the depth of tablets exposed to the incoming stream. The discharge from the tablet chamber then flowed straight through an unbaffled 60-liter contact tank. In tests with the residual chlorine level at 10 mg/l the coliform density of the liquid exiting the contact tank ranged from 4,600 to 24,000 MPN/100 ml. When the collected sample was held in the sampling flask for an additional 10 minutes to allow further equivalent contact time, the coliform density decreased to 40 MPN/100 ml; at a total of 30 minutes of holding time in the sampling flask the density decreased to less than 30 MPN/100 ml. These results indicated the need for an effectively longer duration contact time, on the order of 15 to 20 minutes, to insure the required reduction in coliform density. The mechanical performance of the chlorination unit showed the feasibility of essentially automatic control of the addition of chlorine using a simple system with no moving parts.

Waste Treatment System with Coagulants

To overcome the difficulties observed in filtering wastes containing significant amounts of particles below 30 microns, various coagulants were tested with the MSF system. Initially, standard jar tests were performed to determine the optimum pH and dosage requirements for several selected coagulants. The mixing, flocculation, and settling times of the jar tests were adjusted to conform to those times expected in the full scale treatment system.

Samples of raw sewage were obtained from the inlet feed tank of the MSF system. Each sample was then subdivided into five 200-ml portions and transferred to 400-ml glass beakers. Varying amounts of coagulant were added to each 200 ml raw sewage sample, stirred rapidly for 2 minutes, and then flocculated for 10 minutes with slow stirring, and permitted to settle for 5 minutes. The effectiveness of each coagulant dosage was evaluated by determining the turbidity of the supernatant liquor with a Hach laboratory turbidimeter.

The results of jar tests are summarized in Table 9. The best results were obtained with lime and caustic; however, in each case the pH had to be raised above 11.5. It should be noted that this pH corresponds to a saturated lime solution and that further addition of lime results in precipitation of calcium hydroxide, and does not improve coagulation. Other coagulants generally produced a slowly settling floc; the resultant clarity of the supernatant liquors was inferior to those observed with either lime or caustic.

Based on jar test results, four coagulants, namely lime, caustic, Magnafloc 521-C and Permafloc C-7, were selected for testing with the full scale system. The actual effectiveness of each coagulant was determined by adding coagulants to the raw sewage in the feed tank and processing this mixture through the full scale treatment system in the normal manner.

TABLE 9

COAGULANT JAR TESTS

Coagulant	Dosage Range Investigated (mg/l)	Dosage Giving Best Results (mg/l)	Supernatant Liquor (pH)	Remarks
Lime (CaO)	350 - 3700	1320	11.7	Settles in less than 5 minutes; supernatant liquor clear.
Caustic (NaOH)	400 - 4000	2000	11.9	Settles in less than 5 minutes; supernatant liquor clear.
Alum	2 - 50	20	--	Slow floc formation.
Magnesium Chloride	10 - 50	20 - 30	--	Does not settle in 5 minutes; floc sticks to walls.
Ferric Chloride	10 - 75	30	--	Supernatant liquor not clear.
Primafloc C-7	5 - 100	75	--	Does not settle completely in 5 minutes.
Magnafloc 521-C	5 - 100	75	--	Does not settle completely in 5 minutes.

In these tests a measured amount of raw sewage was delivered to the feed tank by the vacuum transfer system and the required amount of coagulant was added to bring the concentration to the desired value. The coagulants were well-mixed with approximately 8 liters of tap water and introduced to the tank in a single application. The raw sewage with coagulant was allowed to remain in the feed tank for 15 minutes before processing began. The only mixing which occurred within the feed tank was induced by the air admitted to the bottom of the feed tank during each cycle of the single cavity rotary feeder.

The results of these tests series are indicated in Table 10. All SS and BOD levels were determined in the same manner as in the preceding test series, and a material balance was used to determine the solids in the raw feed.

Filter operation was impeded in preliminary operation with lime, and no test data could be collected; the use of excessive amounts of lime, over 3 gm/l, caused blinding of the moving screen and temporarily stopped the system test. Also, after several tests, using lesser amounts of lime as a coagulant, a discrepancy in the material balances was observed. Additional tests were run to verify the imbalance of input solids to the feed tank and the solids output collected at the MSF. Analysis of the tests indicated that a portion of the solids which were expected in the calculated raw sewage feed to the MSF were not accounted for; consequently, the feed tank, which normally was kept sealed for odor control, was opened. Approximately 5 kg of wet solids were collected from the bottom of the tank. These solids which adhered to the tank's shallow sloping bottom were apparently the result of efficient and rapid coagulation of the sewage. The use of lime did produce a significant improvement in the SS removal efficiency of the MSF, with the average efficiency at approximately 88%. Also, the addition of the rapidly coagulated but trapped solids would have increased the efficiency of the MSF to above 90%.

In a separate test, shown last in Table 10, the solids precipitated by addition of lime were observed to pass completely out of the well-cleaned collection tank and into the treatment system. The resulting overall SS removal efficiency across the MSF was 92%. This indicated that lime has the potential for effective coagulation of sanitary wastes even after mechanical agitation has reduced a portion of the wastes to particles below 30 microns in diameter. In comparison to other coagulants tested, namely, caustic and polyelectrolytes, lime appeared superior for removal of suspended solids by the MSF.

The solids removed and collected by the waste treatment system, both with and without coagulant additives, were found to contain between 1% and 8% dry solids per gram of collected solids. This amount of dry solids constituted between 40% and 90% of the suspended solids in the total waste feed to the treatment system.

TABLE 10

SS AND BOD REMOVAL TESTS: MSF TREATMENT SYSTEM WITH COAGULANT ADDITION

Test Volume (liters)	Coagulant & Amount (gm/l)	Suspended Solids (mg/l)			BOD (mg/l)		
		Raw (Feed)	MSF (Effluent)	Carbon Bed (Effluent)	Raw (Feed)	MSF (Effluent)	Carbon Bed (Effluent)
530	CaO 3.42	1905	105	80	510	248	10
378	CaO 1.80	749	123	10	517	300	42
378	CaO 1.80	550	68	4	---	---	---
570	CaO 1.20	649	260	26	---	---	---
378	NaOH 1.13	294	146	50	278	120	57
720	NaOH 1.13	669	200	70	735	368	50
490	-1- .075	236	145	39	---	---	---
378	-2- .025	230	128	44	---	---	---
530	CaO 1.92	1730	139	86	---	---	---

-1- Magnafloc 521-C, 75 mg/l
Alum, 75 mg/l

-2- Permafloc C-7, 25 mg/l

The slurry of collected solids had the flow properties of a sand-clay and water mixture. Visual assessment of the slurry suggested that transport to a collection or disposal site would require positive pumping and that simple gravity flow through normally pitched piping would not be adequate. However, collection is feasible without pumping if a container can be located directly below the accumulation trough at the discharge end of the moving screen filter belt.

The collected solids had the characteristic odor of untreated human wastes, except when lime or caustic were used as coagulants; the wastes had essentially no odor when these additives were employed.

Storage of solids for more than several hours prior to disposal for final processing would require the addition of a suitable bactericide or growth inhibitor to prevent decomposition and attendant gas formation and odor generation problems. Prior experience with incineration of human wastes indicated that the slurry of collected solids is compatible with incineration requirements and should be readily handled with available incineration equipment.

The performance of the carbon beds for BOD removal was satisfactory, and with the MSF gave an overall BOD removal of 92% to 98%, although inlet SS loadings were still above the 100 mg/l level desired for continuous operation. Six carbon adsorption beds were used in tests with coagulants; the beds were arranged in two parallel lines of three beds in series, all in upflow, containing 0.55-0.65-mm carbon granules. However, after processing approximately 3,000 liters of MSF liquid effluent containing either lime or caustic, the inlet carbon support screens of each of the first two carbon columns became clogged sporadically with microscopic fibrous material. The origin and nature of the fibrous material was not readily apparent. Operation of the carbon beds up to that point had been superior to prior operating results, and no evidence of pressure drop change showing plugging within the carbon beds was noted.

During the second to fourth tests listed in Table 10 the effluent from the carbon beds was passed through the water-syphon and tablet chamber and into the chlorination contact tank. In contrast to the prior chlorination equipment configuration, performance was satisfactory and no interference in chlorine residual level was noted with lime or caustic coagulants.

In a separate test with lime as the coagulant the carbon bed effluent was tested for coliform and viable organism content prior to chlorination. This test showed the coliform MPN below 30, apparently due to the high pH, but with the viable organism count above 24,000; for the same effluent after chlorination in the syphon system and contact tank both the coliform MPN and the viable organism count were below 30. The waste treatment system tests were completed with the final tests using lime as the coagulant.

SECTION VI

EVALUATION OF SYSTEM PERFORMANCE

The system performance tests presented in the previous section indicated the general experimental results of operating the MSF waste treatment system under varied feed and operation conditions. The narrative comments included with the experimental data were intended primarily to clarify the data and to show the methodology used in testing of the system and components. The evaluation of system operation presented in this section discusses the significance of system performance, and the overall operating ability of the system to achieve 90% reduction of SS and BOD levels and reduction of coliform below the 240 MPN/100 ml level.

The capability of the MSF waste treatment system to remove suspended solids and biochemical oxygen demand was evaluated with a variety of feed wastes compositions, with several modes of delivery wastes to the system, and under several significantly different system component arrangements. Both SS and BOD removal efficiencies were found to be directly related to particle size distribution; particle size in turn was related to initial waste composition, mode of delivery, and the effect of coagulant. The different waste compositions tested were: (1) food wastes alone; (2) toilet wastes alone, namely feces, urine, and toilet tissue; and (3) food wastes combined with toilet wastes. The different modes of delivering wastes to the system were (1) simple gravity feed, (2) processing through home-type garbage disposal macerator combined with gravity feed, (3) macerating and centrifugal pumping, and (4) lifting toilet wastes by pressure differential (vacuum chamber) combined with gravity feed. During testing the different treatment system component arrangements were (1) the basic system, namely MSF, carbon beds, and chlorinator, (2) basic system with a bed filter after the MSF, and (3) system with coagulants added to feed wastes immediately ahead of the MSF. Tests described were conducted with both the laboratory scale system, and with the full scale system. Although the laboratory and full scale systems differed significantly in mechanical features, their overall performance capabilities were highly similar, and the tests results with one system were directly relatable to those of the other.

Suspended Solids Removal

The MSF by itself is capable of removing essentially all particulates greater than 30 microns in diameter; this size is the effective pore size of the filter screen. In processing unpumped or unmacerated toilet wastes with gentle gravity transport, the SS removal efficiency was estimated at 95%; but for macerated, high-velocity transported or centrifugally pumped toilet wastes, 40%-50%. In processing a mixture of equal parts of food and toilet wastes the SS removal efficiencies were essentially the average for the type of feed and delivery mode

to the system. For example, with a mixture of food wastes and toilet wastes macerated and pumped to the basic treatment system, the overall SS removal efficiency was 65%-70%.

Initial tests in the program demonstrated that the screen filter could readily and continuously remove particles above 30 microns in diameter with over 90% efficiency. The continuous belt filter screen removed solids, a scraper or rotating brush removed the filtered solids, sprays cleaned the moving screen, and the process operated properly on a continuous basis without harmful effects on the screen or hydrophilic sponge materials.

Different modes of delivery of wastes were tested because various methods of waste transport were anticipated aboard ship. The most stringent transport conditions were considered to be maceration and pumping. Consequently, synthesized feed mixtures were macerated and pumped to the treatment system in tests to show pumping effects on the SS removal efficiency.

The inlet feed was synthesized from food wastes and toilet wastes to have SS and BOD levels approximating 750 mg/l. The amount of feces, urine, and toilet tissue were added to feed water in amounts proportional to the normal amount of these wastes generated by one man per day, assuming an average water usage rate per man of 130 l/day. Food wastes, including soap, were added to bring the calculated SS and BOD levels to the desired level of 750 mg/l. This level was selected on the basis of a shipboard usage rate of 130 liters per day, and the assumption that the SS and BOD levels would be based essentially on the 250 mg/l average for municipal treatment system influent but adjusted from the 380 liters per cay per capita usage rate to the 130 liters per day usage rate aboard ship.

Tests with macerated and pumped wastes fed to the basic treatment system (MSF, carbon beds, and chlorinator) showed that system performance was well below the desired 90% SS removal capability, ranging from 45% to 70%. Three different techniques were then tested to improve SS removal efficiency of the MSF system:

1. Addition of a pressure bed filter between the MSF and carbon bed,

2. The use of vacuum transport and gravity feed for toilet wastes only,

3. The addition of coagulants to feed wastes entering the screen filter.

In treating synthesized mixtures of food wastes and toilet wastes the MSF was found to be capable of reducing the SS level only to the 200 to 250 mg/l range. The feasibility of a bed filter was evaluated for lowering the SS level to the 75 to 100 mg/l range. A pressure bed filter was found more effective than a gravity bed filter. Operation with the pressure bed filter demonstrated that this type of filter could lower the SS level to the desired range. The filter was capable of removing 50 to 75% of the particles below the 30 micron size which passed through the screen filter. The effectiveness of the pressure filter bed was due to its ability to remove particles that were predominantly in the 1 to 2 micron size range. These small particles were formed almost exclusively in the mechanical breakdown of fecal wastes during pumping or turbulent transport and constituted the bulk of the solids which passed through the 30-micron pores of the screen filter. The bed filter operated on a cycled basis with backwash after four to six hours of operation, depending on final pressure drop across the filter. The filter media consisted of compressible polystyrene granules which operated to extend the available filtering time per cycle by compressing after layers of the bed gradually filled with filtered particles. The compressed particles allowed additional space for incoming liquid transport and minimized the rate of buildup of pressure drop across the bed.

The pressure bed proved to be a definitely effective method of reducing the SS level. However, sustained operation resulted in a build-up of slime in the filter media. During backwashing the slime interfered with removal of filtered particles, and caused agglomeration of the media. The process of slime build-up could possibly be inhibited by sporadic aeration of the filter, or by the use of additives to inhibit growth in the filter. Because the overall waste treatment system complexity would be increased by both the pressure bed filter and attendant automatic controls for operation and slime inhibition, other techniques with simpler components were evaluated for achieving the desired level of SS removal efficiency.

The next method evaluated was vacuum transport and gravity feed of toilet wastes to the basic treatment system (without the pressure bed filter). It was postulated that if toilet wastes could be transported without significant mechanical break-up, the MSF would be capable of an SS removal efficiency of 85% to 90%, with efficiency higher than 90% for a mixture of toilet wastes and food wastes.

For toilet wastes transported directly from a sump connected through 10 meters of soil lines to a standard lavatory facility, inlet SS levels ranged from 250 to 2000 mg/l. Vacuum transport through 15 meters of 3.5 cm pipe to a collection tank, and gravity feed to the MSF showed a substantial increase in average SS removal efficiency

from the 45% to 50% level up to the 65% to 70% level. These performance tests demonstrated, in a generally quantitative manner, the effect of the toilet wastes transport mode on SS removal efficiency. From these results, it is anticipated that where toilet locations and drain piping can be appropriately located to provide essentially low-velocity and gravity flow of toilet wastes to the treatment system, the suspended solids removal efficiency for the mixture of food wastes and toilet wastes would approach the 90% level.

After sufficient tests with vacuum transport and gravity feed of toilet wastes showed the basic MSF treatment system could achieve an SS removal efficiency of only 65% to 70%, the next method evaluated entailed adding coagulants to the toilet wastes just prior to feeding into the MSF. A series of coagulants were evaluated in jar tests to demonstrate their ability to coagulate and settle these wastes after vacuum transport and gravity feed to the MSF feed collection tank.

The jar tests conducted indicated that lime (CaO) and caustic (NaOH) were the more effective of the six coagulants tested, although two polyelectrolytes tested also showed some degree of coagulation and settling of wastes. The amounts of lime and caustic needed to raise the pH to the 11 to 12 range were significantly greater than the amounts of polyelectrolytes required. On that basis all four candidate coagulants were tested.

Operation of the basic MSF system with manual batchwise addition of coagulants showed that an SS removal efficiency across the screen filter alone of 85% to 92% was feasible when lime was used as a coagulant, and 80% to 85% when caustic was used. The efficiency across the screen filter was in the 60% to 70% range with polyelectrolytes, indicating essentially no improvement over operations without these coagulants.

The overall results indicated favorable feasibility for using coagulants to achieve 90% effluent removal of suspended solids by the screen filter. However, the use of lime did coincide with build-up of a fibrous material in the carbon support screen and plugging of the inlet to the carbon adsorption beds used for BOD removal. Test results (discussed under Biochemical Oxygen Demand Removal) were not conclusive in determining whether this plugging of the support screen was of sufficient severity to preclude operation with lime. The use of coagulants would entail a coagulant feed subsystem consisting of an automatic feeder and controls to proportion the input rate of coagulant to the wastes feed rate.

The collected solids from operation of the MSF with or without coagulants will require pumping to a storage or disposal site. For storage, a germicide would be needed for odor and gas generation control; however, the solids slurry as collected appeared directly suitable for incineration without further treatment.

Removal of Biochemical Oxygen Demand

The BOD removal efficiency of the MSF treatment system was related to both the solids filtering and soluble organics adsorption capabilities of the system. The removal of suspended solids directly reduced the overall BOD level, but also influenced the performance of the carbon adsorption beds which removed soluble BOD from the waste liquid streams.

Although the total time for contact of the liquid stream with the adsorption bed is the dominant factor in BOD removal efficiency, several other factors directly affected performance of the sorption beds, namely SS level to the carbon beds, flow direction in the bed, and carbon granule size.

The concentration of suspended solids leaving the filtering section of the waste treatment system and entering the carbon adsorption beds ideally should be zero to prevent plugging in the beds. As an empirical guide based on recommended operating procedures from manufacturers of activated carbon, an acceptable average inlet SS level should approximate 50 mg/l and should not exceed 100 mg/l. These levels are considered appropriate to prevent mechanical plugging of the carbon bed before its solubles adsorbing capacity is reached.

In initial tests with the basic MSF system and a pressure bed filter using macerated wastes,the SS level to the two carbon adsorption beds in series averaged 85 mg/l, and the carbon beds reduced the incoming BOD level from the 200-350 mg/l range down to the 50-100 mg/l range. Combined with the MSF and pressure bed filter the overall BOD reduction through the complete treatment system averaged 90%.

Subsequent tests with the MSF and pressure bed and centrifugally pumped wastes were not as efficient and with inadvertently lower feed SS and BOD levels, the BOD removal efficiency of the system dropped to the 60% level. The two carbon beds reduced the BOD level from an average input level of 150 mg/l to an average output level of 95 mg/l.

Operation of the MSF without the pressure bed filter but with vacuum transfer of wastes resulted in an average SS input level of 215 mg/l to the carbon beds. Under these conditions the one or two carbon beds used reduced the BOD level from an average 292 mg/l to 206 mg/l, while the overall BOD removal efficiency for the complete treatment system again averaged 60%.

During tests where coagulants were added to the wastes entering the MSF treatment system, the SS level entering the carbon beds with lime as a coagulant ranged from 100-125 mg/l, and with caustic, from 150-200 mg/l. In these tests two parallel columns of three carbon beds in series treated the MSF effluent liquid and showed markedly improved BOD removal capabilities, although data was available from only a short series of tests to demonstrate this performance. The average BOD levels were reduced from 275 mg/l to 25 mg/l with lime coagulant, and from 250 mg/l to 50 mg/l with caustic coagulant. The overall BOD removal efficiency for the complete treatment system approximated 90-95%.

On the basis of these results from the total test program, the MSF treatment system demonstrated an ability to reduce the BOD level of 90% or greater, during specific test conditions. However, in a significant number of tests the removal efficiency averaged 60%, primarily because the influent SS level and corresponding BOD level to the carbon adsorption beds were excessively high, in the 200 to 400 mg/l ranges, respectively, which are in excess of the loadings recommended for adequate removal in continuous operation. These levels were beyond the inherent capability of the carbon columns, and the ability of the carbon columns to provide these substantial removal efficiencies over extended periods is questionable.

The use of a pressure bed filter with the basic MSF system demonstrated that 90% BOD removal efficiency is feasible; the use of coagulants demonstrated a similar system capability. The operating life of the carbon adsorption columns was not adequately demonstrated, primarily due to the fluctuation in influent SS levels to the carbon beds and subsequent plugging of the beds.

The longest testing period for a single carbon bed was approximately 40 hours of cumulative operation. The nominal BOD removal capacity varies from 50 mg/l to 350 mg/l during this period; testing was discontinued because plugging had occurred and pressure drop across the bed was prohibitive. Valid duration tests could not be conducted, and only an extrapolation of the rated capabilities of the carbon adsorbent material can be made.

The nominal capacity of the carbon adsorbent for BOD is 0.3 to 0.8 gm per gm of carbon, in this case Calgon #400 granular activated carbon. In the six -column array used during system tests with coagulants and an adsorption of 250 mg/l of BOD for 3.8 liters per minute continuous flow, the carbon beds would last from 10-30 days depending upon actual inherent adsorbent capacity.

Reduction of Coliform

During the various modes of testing conducted with toilet wastes in the feed stream to the MSF treatment system, the coliform content of the final effluent was effectively controlled initially with addition of a liquid solution of sodium hypochlorite, and finally with solid tablets of calcium hypochlorite. The addition of chlorine in a water solution required a flow control and feed system, while the use of solid hypocholorite tablets in a tube and syphon chamber entailed no moving parts.

With both methods of chlorination a baffled chamber was used to provide 15 to 20 minutes of contact time after chlorination. By maintaining an effluent chlorine residual concentration of 0.6 to 2.0 mg/l the coliform count was readily maintained below 240 MPN/100 ml, with values typically below 30 MPN/100 ml. A concentration of approximately 50 mg/l of chlorine was needed in the influent to the contact chamber.

The performance of the hypochlorite basket and syphon-tube chamber system was demonstrated as a highly satisfactory mechanism for automatic chlorination on a demand basis. The amount of hypochlorite tablets estimated for normal operation would approximate 2.3 kg per week.

SECTION VII

ECONOMIC ANALYSIS

Although the treatment system was not actually evaluated on a marine vessel, projected costs can be estimated for a vessel with a full time crew of 15 men. The vessel configuration is based on a modern vessel with all waste piping routed to a central waste treatment compartment.

The total cost of the waste treatment system includes the following:

1. Cost of system hardware
2. Installation cost
3. System expendables and operating expense
4. Normal maintenance
5. Handling and disposal of accumulated waste solids.

Not included is the value of the space which the treatment system occupied.

Cost Assumptions

System hardware costs are based upon costs incurred in the building of the full size prototype. The costs of newly developed components fabricated during this program are estimated on the basis of limited production runs.

The unit was designed in separable modules which will pass through a 76-cm wide by 152-cm high hatch. In estimates for the installation it was assumed that the complete system could be assembled within the vessel without disassembling the modules or cutting of the ship's deck or hull. It was also assumed that only a minimum of the ship's piping would require alteration to accommodate the system and that all waste lines would gravity drain to the inlet feed tank.

The expendable items included in the estimate are the MSF belts (screen and sponge), granular activated carbon, lime, and hypochlorite tablets.

Belt life was estimated at two months. Activated carbon consumption was estimated at 45 kg per month. Hypochlorite tablet usage was estimated at 2.3 kg per week. The cost of lime is based upon an expected usage rate of 1.4 gms per liter.

Insufficient operating data was accumulated to accurately estimate the total maintenance requirements for the system; however, studies were performed to estimate time requirements for known maintenance items. It was found that both belts could be replaced in approximately 4 man-hours and a carbon column could be removed, refilled, and replaced by one man within an hour. For purposes of this estimate it was assumed that each of the three pumps in the system will be replaced after one year's service and that the complete system will be overhauled annually.

In estimating the cost of handling the accumulated solids which are removed from the waste stream, two options were considered:

1. Storage aboard the vessel with pump-out to shore facilities on a weekly basis (2 man-hours per week).

2. Onboard incineration of solids using a small shipboard incinerator currently under shipboard evaluation.

System Costs

The itemized costs of the system hardware and installation together with the per annum costs for operating, maintenance, and solids handling based on these assumptions are presented below.

SYSTEM HARDWARE

Main sewage storage tank (Complete with lining, level control, and manual shut-off valve)	$1000
Rotary feed valve (Complete with motor drive and slip clutch)	800
Moving screen filter (Complete with drive, slip clutch, and primary feed pump)	5000
Pressure filter (optional)	1200
6 Carbon adsorption columns	1000
Chlorination system	200
Control cabinet	500
TOTAL	$9700

INSTALLATION

Labor

Belt replacement (24 man-hours at $8.00/hr)	$ 192
Carbon (72 man-hours at $8.00/hr)	576
Miscellaneous repair (25 man-hours at $8.00/hr)	200
Annual overhaul (20 man-hours at $8.00/hr)	160
Yearly Labor Total	$1128

Material Replacement

Pumps & motors	$ 300
Spray nozzles	10
Drive chain	10
Miscellaneous	30
Yearly Total Materials	$ 350
TOTAL MAINTENANCE	$1478

HANDLING & DISPOSAL OF SOLIDS (per year)

Onboard storage & weekly pumpout	$ 832
Labor (104 man-hours per year at $8.00/hr)	
Service Charge (52 pumpouts at $5.00 each)	260
	$1092

Onboard Incinerator

Capital cost incinerator	$6000
Installation	2000
Fixed Cost	$8000

Operating Cost/Daily

Fuel oil, 30 l/day @ $0.04/l	$ 1.20
Power, 24 KWH/day @ $0.04/KWH	.96
Daily Total	$ 2.16
YEARLY OPERATING COST	$ 758

Amortized Costs

The annual costs of the system based on an expected 15-year system life including the solids handling costs for both storing onboard and incinerator options are presented as follows.

The cost of the system hardware was estimated at $9700 and the installation cost of $4800 giving an initial fixed cost of $14,500 over a 15-year life expectancy of $967 per year average fixed cost. Operating and maintenance are $1382 and $1478, respectively, bringing the cost to $3287, exclusive of solids handling costs.

Onboard storage with weekly pumpout would add an additional $1092 per year and bring the total annual cost to $4919 for this option.

The fixed charges for an onboard incinerator were estimated at $8000, which over a 15-year operating life would be $533 per year. Operating costs for the incinerator were estimated at $785 per year to bring the total annual cost of the treatment system complete with onboard incinerator to $5145.